**Modeling the Relation of Hand-Arm Vibration Exposure and Occupation Characteristics Using Occupational Health and Safety Administrative Data**

Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of Master of Science
In the Department of Community Health and Epidemiology
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Saskatoon

By

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**Abstract**

*Background*

Hand-arm vibration (HAV) is an occupational hazard which, cumulatively, leads to hand-arm vibration syndrome (HAVS). Detection and reduction of HAV can help prevent the disease or slow down its progress. Unfortunately, assessment of HAV through direct measurement is difficult due to the high cost of measurement equipment, interruption of work performance, and long travel cost to worksites. An alternative assessment method is through development of an exposure prediction model to identify workplace, tool, and task characteristics which significantly predict HAV exposure.

*Purpose*

The purpose of this study is twofold: 1) to determine the extent and nature of previously published scientific journal articles on exposure prediction modeling of HAV through performing a systematic review; and 2) to develop a new exposure prediction model using administrative data to find significant HAV predictors.

*Methods*

A systematic review of relevant studies involved humans aged 18 or over, applicable to occupational setting, with vibration measured using tri-axial accelerometer and statistical modeling of the effects of occupational characteristics on measure HAV were identified. Five online bibliographic databases (Medline, CINAHL, Web of Science, Scopus, and EMBASE) were searched using a combined word list of terms under three categories: “occupational diseases”; “Hand-arm vibration”; and “Statistical Modelling”. Two multiple linear regression models predicting average hand-arm vibration exposure over 8 hour day, A(8), were built using enforcement data collected by Ministry of Labour Relations and Workplace Safety Saskatchewan using standard model building method. In addition, GEE was used to account for repeated data collection within workers and worksites.

*Results*

In the first manuscript, 7 articles found were deemed relevant. Four studies built regression models, while three used ANOVA to find significant HAV predictors. Examples of significant HAV predictors included: tool age, tool weight, participant, and operating power; the proportion of HAV variance explained varied from 46 to 90%. In the second manuscript, the models based on administrative data explained 16% to 27% of A(8) variance. The included variables were tool power source, vibration control, and job type for the parsimonious model; the comprehensive model has the same variables as parsimonious along with accelerometer attachment method and tool brand.

*Conclusion*

HAV prediction through exposure prediction modeling is a relatively new method for assessing occupational HAV. It is feasible to find HAV predictors using low-cost administrative data, and variables such as tool power source, job type, and vibration control make promising predictors. However, the variance explained will be lower than using data collected for research purposes. The significant predictors found in the systematic review can be considered when installing protective measures in the future. The significant predictors found and procedures used from the modeling study can be considered for future HAV exposure prediction modeling studies.

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## Table of Symbols and Abbreviations

| | |
|---|---|
| A(8) | Average hand-arm vibration exposure over 8 hour day |
| ACGIH | American Conference of Governmental Industrial Hygienist |
| CCOHS | Canadian Centre for Occupational Health and Safety |
| EAV | Exposure action value |
| ELV | Exposure limit value |
| HAV | Hand-arm vibration |
| HAVS | Hand-arm vibration syndrome |
| HSE | Health and Safety Executive |
| ISO | International Organization for Standardization |
| LRWS | Labour Relations and Workplace Safety |
| NIOSH | National Institute of Occupational Safety and Health |
| OSHA | Occupational Safety and Health Administration |

## Chapter 1: Introduction

Hand-arm vibration (HAV) exposure is an under recognized occupational hazard that can nevertheless be devastating when unmonitored. Over-exposure to HAV can lead to a collection of debilitating occupational diseases collectively called hand-arm vibration syndrome (HAVS). HAVS involves vascular, neurological, and musculoskeletal damage to the hands caused by prolonged HAV exposure from use of vibrating tools such as drills, chainsaws, screw guns, and more (Weir & Lander, 2005). There are evidence that the diseases' occurrences are influenced by the workers' age and sex. Age is a contributing risk factor along with smoking and other pre-existing medical conditions that cause neurovascular pathology (Burström, Järvholm, Nilsson, & Wahlström, 2010). Males tend to develop HAVS more than females, possibly due to the higher likelihood of tool-heavy professions being dominated by males (Falkiner, 2003). It is interesting to note that although sex and age are risk factors for HAVS, they may also impact HAV exposure. It has been reported that the number of people exposed to HAV at work exceeds 150 000 in the Netherlands, half a million in Great Britain, and 1.45 million in the United States (Bovenzi, 2011). According to epidemiological data, it is estimated that about 50% of workers exposed to HAV have or will develop HAVS (Bernard, Nelson, Estill, & Fine, 1998). Due to the lack of an objective diagnostic method for HAVS, there are substantially more cases of undiagnosed HAVS, but the diagnoses are increasing. In the United Kingdom, the number of newly recorded cases of vibration induced white finger (VWF) assessed for Industrial Injuries Disability Benefit was 1045 from 2009 to 2010, which is an increase from 850 in 2008 – 2009 (HSE, 2012b); this continues to be significantly lower than the expected number of 250 000 cases.

Like other industrial countries such as Great Britain, HAVS in Canada is underreported by workers and health professionals due to the intermittent nature of symptoms (occur most frequently when hands are cold or wet), workers being unfamiliar with the potential seriousness of HAVS, and lack of trained physicians who can distinguish HAVS from other medical conditions with similar symptoms ; the number of reported occurrences also differ substantially between provinces due to the nonexistence of an objective clinical test for HAVS and differing interpretation of signs and symptoms (CCOHS, 2008; McDowell, Dong, Xu, Welcome, & Warren, 2008). As of 2006, 10% of Canadian manual workers experienced exposure to HAV, which is 1% of the overall workforce (equivalent to more than 1.6 million exposed workers) (CCHALW, 2009; CREOD, 2010). However, in Ontario the number of people with diagnosed HAVS were estimated to be around 1000 from 2003 to 2008 with nearly 900 HAVS compensation claims were accepted, while only 5 were accepted in Saskatchewan during that time period (Thompson, Turcot, Youakim, & House, 2011). Despite the low number of documented HAVS cases, Saskatchewan's economy is heavily dependent on its construction, mining, and forestry industries, which use the highest proportion of the province's labour force in the province (13% of Saskatchewan's total labour force with a combined labour force of 73,800 workers as of March 2013) (StatsCan, 2013). These industries also involve high usage of hand-held vibration tools. Saskatchewan currently produces one-third of the world's potash and uranium, and the employment rate in construction has increased 70% since 2001. In addition, 33.9 million hectares of Saskatchewan land is forest (52% of entire provincial land) and 37% of the forest land is commercial forest. Saskatchewan's commercial forestry sector contributes over 1 billion dollars per year to the provincial economy, which employs as many as 5000 people during normal market periods (Harada & Mahbub, 2008). With Saskatchewan's economy being heavily dependent on these industries, without effective assessment and safety precaution in place, potential losses to health, productivity, and the overall economy could happen due to HAVS developed from the HAV exposure.

The dependence of Saskatchewan's economy on these industries involving high usage of hand-held vibration tools shows a need to develop an economical method to prevent HAV exposure among Saskatchewan's working population. To effectively prevent HAV exposure in aiding prevention of the progression and development of HAVS amongst workers, it is necessary to find more economical methods to evaluate HAV in the workplace. Nonexistence of objective HAVS diagnosis method means there is no known accurate way of pinpointing the actual HAVS burden in Saskatchewan, therefore prevention of the disease is important. The path to HAVS prevention involves four steps: 1) Injury surveillance (estimate the extent and nature of HAVS); 2) Exposure assessment methodology; 3) Epidemiological studies determining how exposures contribute to HAVS; and 4) Interventions designed to decrease exposure and preserve health. Since it is difficult to estimate the extent of HAVS in the population due to the difficulty of making the diagnosis, it is wise to focus on step 2 – the exposure assessment methodology (ACGIH, 2012).

Currently, the gold standard of assessing occupational HAV exposure is through direct field measurement. This requires going to the job site and using a tri-axial accelerometer connected to a data-logging three-channel vibration monitor that meets the requirements of ISO-

8041 for accurate measurement of tool vibration output in accordance with HAV concerns (ISO, 1990). The accelerometer should be positioned as close as possible to where the tool is held, which is a function of how the worker uses the tool and what task was being performed. The device measures vibration from three orthogonal planes during use (see figure 2). The x-plane should pass through the back of the hand, the y-plane should pass across the knuckles of the hand, and the z-plane should run parallel to the plane created by the metacarpals. The accelerometer should be mounted rigidly in order to obtain accurate and repeatable results; hose clamp adapters are commonly used for mounting (Wolcott, 2004). Although this method is highly accurate, the procedure is expensive and time consuming due to the expense of hiring a measurement professional, measurement equipment costs, and travel to different job sites.

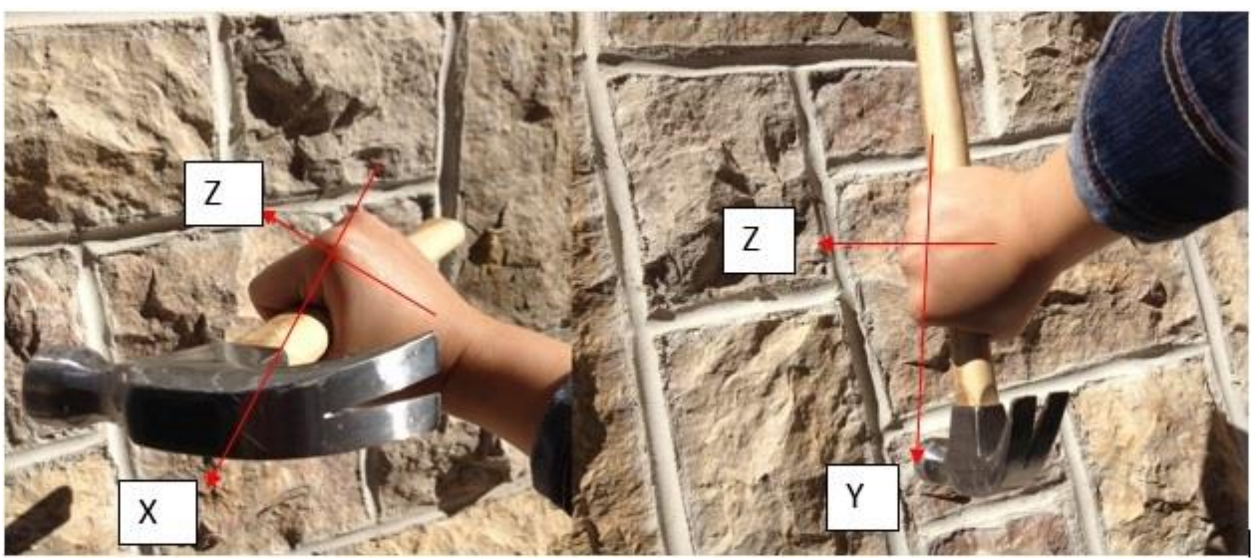


**Figure 1.** Three orthogonal axial planes show how the acceleration of the hand arm vibration are measured simultaneously in 3 directions

In recent years, exposure prediction modeling has been used to find the relationship between measured vibration and occupational characteristics, thereby identifying predictors of a variety of occupational hazards such occupational dust (Burstyn I, 1997), asbestos (Dement, Harris, Symons, & Shy, 1983), and whole-body vibration exposures (Village et al., 2012). For HAV, the process would involve developing a statistical model with measured vibration value as the dependent variable and occupational factors (eg. Tool, worker, and other occupational characteristics) as independent or predictor variables. The identified predictors of HAV can then be used to estimate vibration exposure which can then be controlled to decrease the amount of HAV exposure in the workplace. In addition, in future studies where HAV assessment is needed, it can be performed by using a questionnaire to collect information of the HAV predictors found from the model. Hence, this method has the potential to inexpensively generate a statistical model which will predict HAV exposure as well as identify the significant predictors of HAV exposure that may be avenues for prevention.

Using exposure prediction modeling to estimate HAV exposure and find determinants of exposure is a relatively new field; thus, the scope and number of studies which have involved modeling the relationship between measured HAV exposure and occupational characteristics using administrative data is currently unknown. The contents of this thesis will help to fill the gap in finding the extent of studies assessing HAV exposure through exposure prediction modeling and studying the effectiveness exposure prediction modeling using administrative data through completing the following objectives:

1. Conducting a systematic review to determine the number and quality of studies currently in the scientific literature which involved exposure prediction modeling of HAV
2. To build a HAV exposure prediction model using an administrative dataset

**Chapter 2: Finding the Determinants of Occupational Hand-Arm Vibration Exposure Using Exposure Prediction Modeling: A Systematic Review**

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**Keywords**: Systematic review, Hand-arm vibration, Exposure prediction modeling, Occupational hygiene, Determinants of exposure

## INTRODUCTION

Hand-arm exposure to vibration (hand-arm vibration or HAV) is an occupational hazard which has been shown to lead to debilitating occupational diseases such as vibration induced white finger, Raynaud's syndrome, and other upper extremity disorders - collectively known as hand-arm vibration syndrome (HAVS) (Bovenzi, 2006) ). To effectively prevent HAV exposure in the workplace, it is important to first assess occupational HAV exposure in order to plan and prioritize protective measures; to plan and prioritize protective measures requires understanding the relationship between HAV exposure and occupational characteristics which influence HAV exposure. Although occupational characteristics are relatively easy to obtain, direct measurement of occupational hand-arm vibration is a costly task which involves expensive measuring equipment and long periods of traveling to worksite to perform measurements. Exposure prediction modeling is an alternative method of assessing HAV exposure through finding significant factors which influence hand-arm vibration (predictors of HAV exposure) from statistically modeling the relationship between occupational characteristics and measured HAV. A strong positive aspect of this method is its ability to identify significant predictors of HAV without the need of using large amount of measured HAV data, the significant predictors can then be manipulated to control HAV exposure.

Exposure prediction modeling has been widely used for identifying predictors of worker's exposure to many types of hazardous occupational exposures, including asbestos (Dement JM, 1983) and fungal exposure (Macher JM, 1992) and whole body vibration exposure (Chen et al., 2004; Village et al., 2012). However, it is unknown to what extent has this method been used to find the predictors of HAV exposure, and the level of influence those predictors carry. Therefore, the goals of this systematic review are: 1) to identify and summarize published studies which used exposure prediction modeling to find predictors of HAV, 2) assess and compare the quality of included studies and 3) summarize the significant predictors of HAV exposure within the current literature.

## METHODS

### *Search and Screening*

The relevant literature was identified by applying a list of search terms under three conceptual categories: occupational exposure, hand-arm vibration, and modeling methodology. These terms were developed with the assistance of a health science librarian and applied to five online bibliographic databases: Medline, Web of Science, CINHAL, Scopus, and EMBASE. The search was performed on June 1, 2014. The research websites of the authors of the relevant studies found were checked for additional articles. The sensitivity and specificity of the search was tested through looking for additional papers from websites of authors identified from the relevant literature. The articles found were de-duplicated and screened for relevance by two reviewers in parallel using DistillerSR (Evidence Partners, Ottawa, Canada). The included articles: were in English language, involved direct measurement of vibration using a tri-axial accelerometer in laboratory or occupational setting, used exposure prediction modeling to find significant predictors for HAV exposure, and involved adult (over age of 18) human participants.

## RESULTS

### *Search results*

From the 361 unique titles identified in the search, six articles were found relevant to the objectives of this study. The results of the search and screening procedure are shown in figure 1. One additional relevant article was found from the research website of the authors of one of the 6 relevant articles, which makes a total of seven relevant research studies found.

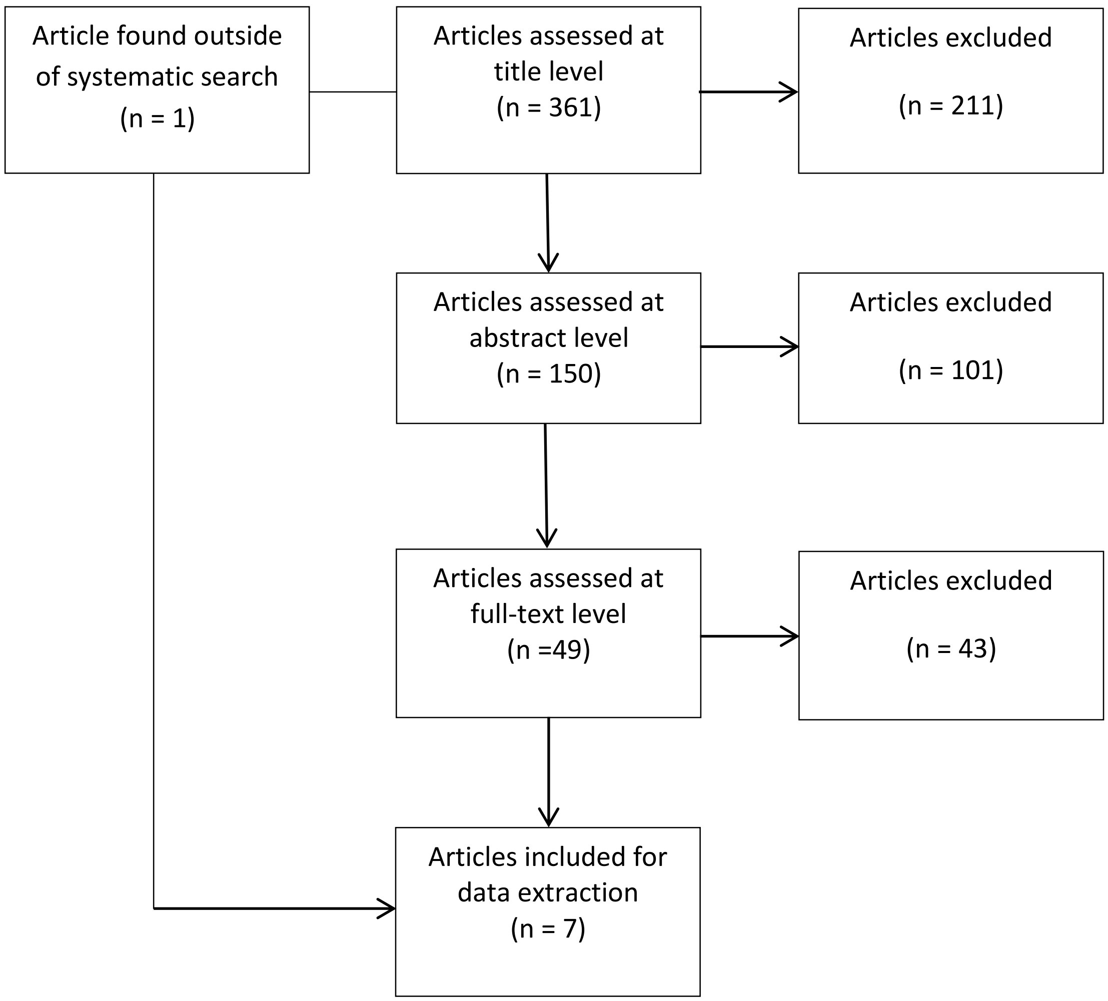


Figure 1: Search Results and Screening Process

*Study Design*

Included articles varied considerably in their objectives, sampling strategies, and measurement methods. Among the seven articles, three study design types were used: 1) vibration measured at worksite as a part of normal work activities (observational studies); 2) vibration measured in simulated study at worksite without randomization of determinants (quasi-experimental studies); and 3) vibration measured in simulated study with randomization of determinants (experimental studies). The objectives of the studies (in the finding HAV predictor perspective) can be separated into 2 categories: 1) Assessing HAV exposure of different tools from different industries (Coggins, Van Lente, McCallig, Paddan, & Moore, 2010; Vergara, Sancho, Rodríguez, & Pérez-González, 2008) or 2) assessing HAV exposure of a certain type of tool (Dewangan & Tewari, 2009; Liljelind et al., 2013; Liljelind, Wahlstrom, Nilsson, Toomingas, & Burstrom, 2011; McDowell et al., 2008; Swuste P, 1997; Vergara et al., 2008).

In general, quasi-experimental and experimental studies more often involved assessing HAV exposure from a certain type of tool, while observational studies were involved in assessing several different tool types. The two experimental (Dewangan & Tewari, 2009; Liljelind et al., 2013) and three quasi-experimental studies (Liljelind et al., 2011; McDowell et al., 2008; Swuste, van Drimmelen, & Burdorf, 1997; Vergara et al., 2008) were all simulated studies, and two studies were observational studies involved in finding HAV exposure predictors for more than one type of tool (Coggins et al., 2010; Vergara et al., 2008). In addition, studies involving multiple tool types did not always perform more vibration measurements than studies involving one tool. The study by Vergara et. al, which involved studying multiple tool types in different industries, had 70 tool measurements, which is less than the total measurements obtained from studies by McDowell et. al (75 measurements) and Liljelind et. al (80 measurements), both studies involved one tool type.

*Correlation Testing and Model Building Methods*

In general, there were gaps in the reporting of statistical methods, including incomplete reporting of correlation testing, modeling method, variances explained by the significant predictors, and the model validation methods. Only one article reported testing correlation between predictor variables (McDowell et al., 2008). Only one of the studies found stated the model building technique used for three studies out of seven where full models were built; two were multiple linear regression models and one was a multiple logistic regression model. These three articles were the only ones which reported the proportion of variance explained by the significant determinants. The four other studies used ANOVA to find the significant predictors towards HAV exposure did not report the proportion of variance explained by each predictor (Dewangan & Tewari, 2009; McDowell et al., 2008; Vergara et al., 2008). In addition, only two studies, by Liljelind et. al (2011, 2013), had validated their models. The goodness-of-fit of these two models was evaluated by investigating the residuals and no strong deviation from the normal distribution was found (Liljelind et al., 2011). For the other study, its model validation method was through minimizing Akaike's information criterion (AIC) during model building (Liljelind et al., 2013).

**Table 1. Summary of Studies of HAV Exposure Predictors**

| Author, year | No. of participants | No. of Measurements | Dataset Collection Environment | Experiment Type | Potential Determinants Documented During Exposure Measurements | Study Participants | Data Analysis Method | Percentage of Variance Explained (%) |
|---|---|---|---|---|---|---|---|---|
| Coggins et. al, 2003 | 289 | 264 | work site | observational | **Tool brand, tool age, tool weight, material worked on** | 20 types of tools were selected, 289 workers participated | Generalized linear models with robust estimation | N/A* |
| McDowell et. al, 2008 | 6 | 75 | Simulated at the worksite | Quasi-experimental | **Participants, tool, participant x tool** | 6 participants with 100 hr of logged work | ANOVA | N/A |
| Liljelind et. al, 2011 | 10 | 80 | Simulated at the worksite | Quasi-experimental | **Operator,** work posture, measurement run, **grinding wheel**, grinder, **operator-grinder interaction** | 10 experienced operators | Mixed effects model (linear) | 58 |
| Swuste et. al, 1997 | 5 | N/A | work site | Quasi-experimental | **Operating pressure**, drill make, **age of drill**, experience of worker, **presence of buffer ring** | 5 building sites | Multiple logistic and linear regression | 46 |
| Vergara et. al, 2008 | 30 | 70 | work site | observational | **Tools (grouped by task),** weight of tool, handle features, work condition (gloves, extreme weather) | 70 tools in 19 companies and 30 workers interviewed | ANOVA | N/A |
| Dewangan & Tewari, 2009 | 10 | 27 | simulated | Experimental | **Direction of operation, operator**, three modes of transportation (tarmacadam road, rota-tilling in untilled field, rota-puddling in submerged field) | 10 experienced operator | ANOVA | N/A |
| Liljelind et. al, 2013 | 11 | N/A | simulated | Experimental | **Brand of grinding wheel,** operator (age, body height, weight, length and volume of hands, max hand grip force, length of work experience), **machine wheel wear**, **time to complete work task** | 11 experienced operators | Mixed effects model | 90 |

*N/A – information not available in study

**Table 2. Summary of Significant HAV Exposure Predictors**

| Author, year | Tool Brand | Age of tool | Tool Weight | Material worked on | Tool Part Maintenance | Time to complete task | Tool Type | Operating Mode (power and direction) | Presence of buffer ring (Y/N) | Participant | Participant-Tools interaction |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coggins et. al, 2003 | [1] | +[2] | [1] | [1] | | | | | | | |
| McDowell et. al, 2008 | | | | | | | Different tool models of the same tool type | | | | Interaction between participant and a tool |
| Liljelind et. al, 2011 | | | | | | | Different tools of the same tool type | | | | Interaction between participant and a tool part |
| Swuste et. al, 1997 | | + | | | | | | Operating power has positive relationship with vibration exposure | Having a buffer ring has negative relationship with vibration exposure | | |
| Vergara et. al, 2008 | | | | | | | Different tool types | | | | |
| Dewangan & Tewari, 2009 | | | | | | | | Increased forward speed has a positive relationship with vibration | | | |
| Liljelind et. al, 2013 | | | | | + | + | | | | | |

[1]Variable significant only for certain tools or in certain situations
[2]Variable has positive relationship with HAV exposure
Shaded regions represent significant predictors of each study

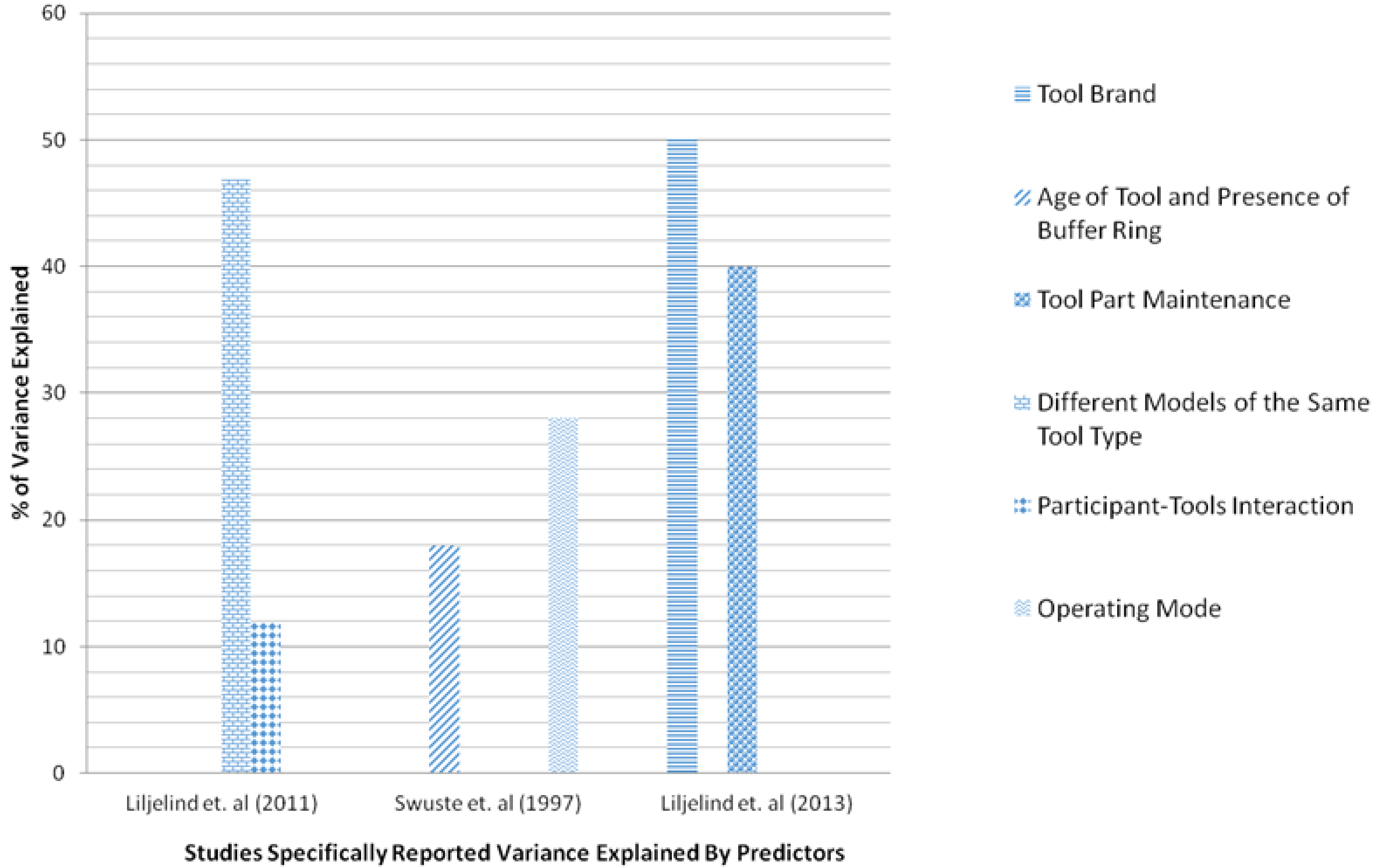


Figure 2. The percentage of variance explained by studies

## DISCUSSION

*HAV predictors*

The description of each article is shown in Table 1. The number of articles found was not sufficient to define a comprehensive pattern of potential and significant HAV predictors found in HAV exposure prediction modeling in the literature, but some patterns did arise within these articles. The potential predictors tested in the articles found can be classified into three categories: 1) tool information (brand, age, weight, power source, operating power); 2) participant information (workers' posture, workers' experience, physical attributes, max hand grip force); and 3) task information (material worked on, time needed to complete task, gloves worn during work). A complete list of significant predictors found by each study can be found in table 2. Tool characteristics were found as potential predictors in all seven articles while only four included participant characteristics as potential predictors. In addition, tool characteristics appeared as potential predictors more frequently in seven articles overall than participant characteristics (21 and 6 times, respectively). Tool characteristics were shown as significant predictors 14/21 times in all studies while participant characteristics were significant 3/6 times.

*Tool Characteristic Predictors*

Table III and Figure 2 displays each articles' description of how significant predictors impacted measured HAV and the percentage of HAV variance explained by individual significant predictors respectively. Tool characteristics were shown to impact HAV exposure due to differences between tool types, different tool models of the same tool type, and different tools of the same model and tool type (all categorized as 'tool type'). Tool brand, age, weight, part maintenance, operating mode, and presence of a buffer ring for pneumatic drills were also tested for significance. Three studies included different tool types (Vergara et al., 2008), different tool models of same tool type (McDowell et al., 2008), and different tools of the same model and type (Liljelind et al., 2011) as significant predictors. The study by Liljelind et. al (2011), the only study to specifically state the variance proportions explained by tool type, showed that 46.8% of variance was explained by differences between the tools of the same tool type and model; also, the interaction term of participant and tools explained 12% of variance. One possible reason for this result is that the tools were differently aged and maintained ; it is possible that these factors led to the significant vibration difference between the tools since these characteristics were found to be statistically important in another study (Coggins et al., 2010). In the McDowell et al. study, a difference in vibration was found between electrical and pneumatic impact drills, consistent with the results of a  previous study where it was shown pneumatic tools have higher vibration levels than electrical tools (Phillips, Heyns, & Nelson, 2007). The Vergara et. al (2008) study suggested that the significant differences observed for vibrations between tool types can be attributed to larger variation in vibration measurements obtained from tool types such as hammers, saws, or drills. This study also found significant differences in levels of vibration generated by the same type of tools where the authors suggested that tool designs should be studied along with tool type in future HAV assessment studies.

Two out of the seven articles looked at the significance of tool brand, age of tool, operating power and direction of the tool operation during measurement as predictors, and each were found to be significant in both studies. The study by Liljelind et. al (2013) stated that brand of tool, along with wheel wear and time to complete work task had a positive relationship with HAV exposure, explaining 90 – 95% of variance, with tool brand explaining ~50% variance and tool part maintenance explaining ~40% of variance. The study stated that two electrical and two pneumatic angle grinders were the tools tested and it is possible that the pneumatic grinders were one brand while the electrical grinders were the other brand led to brand being significant. For wheel wear (a component of tool part maintenance), the authors described that the wheels used for different grinders had different flexibility and wear patterns, which could contribute to differences in vibration. The age of tool was consistently found to be a significant predictor whether it was assessed as a categorical variable (Swuste et al., 1997) or a continuous variable (Coggins et al., 2010), and in both studies was shown to have a positive relationship with HAV exposure. In Swuste et. al, age of tool was shown to explain 18% of variance together with the presence of buffer ring, which had a negative relationship with HAV exposure. Coggins et. al explained that the relationship was probably due to wear and tear associated with older age and damaged or blunt tool parts related to higher vibration emission, and that newer tools are more likely to be ergonomically designed to attenuate vibration. Operating Mode (power level and direction) had a positive relationship with HAV exposure in two articles. Swuste et. al found that an operating pressure at seven bar or above contributed to higher HAV exposure. For Dewangan and Tewari's (2009) study, the operating mode was referring to the direction of the hand tractor's movement and it was shown that higher vibration emission occurred only when tractor was moving forward. The authors believed that the forward movement occurred at the same time as when drivers were performing tasks, which required different strength levels of grip and push force to make sharp turns, thereby contributing to differences in vibration emission.

Tool weight was found significant in the Coggins et. al study, where it was significant only for select tools and was neither a consistently positive nor negative predictor. Although not specifically studying weight, Dewangan and Tewari's (2009) study of hand-tractors suggested that variation in grip and push force of operation (which is a function of the tractor's weight) can influence the amount of HAV exposure. A heavy tool may require a tighter grip to control while performing a task, which will increase the surface area of contact the hand have to the tool handle, which in turn leads to higher vibration exposure.

*Participant Characteristics Predictors*

Participant characteristics were found to significantly influence HAV exposure in three out of the four studies which tested for their significance (Dewangan & Tewari, 2009; Liljelind et al., 2011; McDowell et al., 2008). In Dewangan and Tewari's study of hand-tractors, they stated the significant effect of participants on hand-transmitted vibrations may be due to variation in grip and push force and posture of operation. The tractors often required push/pull force at the handles to maneuver the hand tractor, and the different working techniques amongst participants has been shown to influence severity of HAV exposure in past studies (Radwin, Armstrong, & Chaffin, 1987; Welcome, Rakheja, Dong, Wu, & Schopper, 2004). The interaction between participant and tools was studied and found significant in two studies by McDowell et. al and Liljelind et. al. (2011), with the interaction term of the latter study explaining 12% of variance explained by the interaction. McDowell et. al stated that the variance explained by the participant and tools interaction term was likely to be caused by differences in applied hand forces, postures, and biodynamic responses to the hand-arm system, which was also found in another study (Shida, Nakagawa, Okuno, Maeda, & Yonekawa, 2001).

*Strengths and Limitations*

Currently, little research on statistical modeling of occupational HAV exposure has been performed, which is reflected in only seven relevant studies meeting inclusion criteria were found for this review. The included studies revealed different methods used in hand-arm vibration exposure prediction research, as well as several gaps which can be addressed by future research. Most included studies focused on a single tool type, possibly because the data for a single tool type within a single industry can be collected in a shorter time period, at one place, involving fewer participants, thereby making the study easier to manage and complete. Similarly, a simulated study can be isolated from the actual workplace to prevent interruption and distraction. In terms of modelling methods, multiple linear regressions appear to be current standard practice in building HAV exposure prediction models. However, correlation and model building methods were not well reported in the studies, and none of the studies explicitly described the model building techniques and validation methods used. Rigorous between-variable correlation testing and model building techniques can mean the difference between a robust model and a weak one, which can also influence the qualities of significant predictors selected. It is recommended that future studies include thorough descriptions of correlation testing, model, and model validation methods. Given the reliance on linear regression, it would also be valuable to explore different model building techniques to more accurately find HAV exposure predictors.

It is possible that the articles minimized reporting of correlation testing and model building techniques in favour of reporting on the main goal of the studies: to find significant predictors of

HAV exposure. However, there were inadequacies of reporting the significant predictors found. For example, only 2 studies stated how much variance each significant predictor explained (Liljelind et al., 2011; Swuste P, 1997). Three studies, which used ANOVA to find significant determinants, did not state the separate variance percentage explained by each predictor. On the other hand, three out of the 4 studies which used standard model building methods stated the variance percentage explained by each significant predictor. In order find the relative importance of the determinants, it is important to know the separate proportion of variance explained by each determinant. In addition, there were some predictors which did not repeatedly appear in the seven studies found, but do merited further investigation in the future. For example, tool weight was only shown as a significant predictor in one study out of the two studies found which tested for its significance, as well as in studies which were excluded from the search (Edwards & Holt, 2005; Vergara et al., 2008); similar predictors include tool part maintenance and material worked on.

The search algorithm used for this systematic review was deemed to be sensitive enough for finding studies which used exposure prediction modeling to find predictors of HAV exposure in the work place. When the search was performed, no limits were applied in order to obtain a wide range of articles. Limits were used during the screening process to ensure as many relevant articles were included as possible. One article was found outside of search through citation tracking, although it was determined that it was not picked up in the original search was because it was entered into the database after the search date but was picked up during a rerun search.

In order to develop a search strategy with high sensitivity, long period of time was spent on weeding through articles that would not otherwise be found in the search.  There is no standardized vocabulary which specifically targets this type of study for retrieval in literature searches, therefore it is unknown how many studies precisely have used exposure prediction modeling method for finding predictors of HAV exposure. Time and human resources constraints did not allow hand-searching of all potentially relevant journals. To make the search more sensitive, the search term *ANOVA* was used in the statistical modeling category of search terms, which could have contributed to noise in the articles. However, using exposure prediction modeling to find predictors for HAV exposure is a relatively new area with few studies done; therefore, the gain of finding sufficient studies outweighed the cost of time contributed by irrelevant articles.

*Conclusion*

To our knowledge, this is the first systematic review of exposure prediction of occupational HAV exposure.  Currently there are more simulated studies where measurements were made from one single tool type from simulated work tasks completed by a few participants than experimental studies which involved multiple tool types and large number of participants. Tool characteristics (eg. brand, age, weight, maintenance, and operating mode) more represented as individual variables in studies while participant characteristics (mainly represented by the category participants without subdividing it). Factors such as different tool types and different participants were predictors most frequently found as significant. Among the studies which reported the percentage of variance explained by significant predictors, tool characteristics such as tool brand and maintenance explained 50% and 40% of variance respectively, while participant characteristic predictors explained only 12%.

Future studies investigating exposure prediction modeling of HAV exposure can consider alternative model building techniques to build more robust models and more accurately determine the percentage of variance explained by the significant predictors. It would be important to know the percentage of variance explained by significant tool predictors such as tool weight and tool age. Additionally, participant characteristics such as grip strength and years of job experience can be tested individually in exposure prediction models to see more precisely which participant characteristics contribute to HAV exposure. Furthermore, larger sample size, larger variation of study variables and clearer reporting of study and validation methods can ensure the quality of models built and influence better HAVS studies in the future.

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## Chapter 3: Alternative Exposure Assessment for Occupational Hand-Arm Vibration: Exposure Prediction Modeling Using Administrative Data

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**INTRODUCTION**

Hand-arm vibration syndrome (HAVS) is a debilitating disease which involves symptoms such as numbness of one or more fingers from nerve damage and hand pains caused by damages to the muscles, joints and bones from hand-arm vibration (HAV) through using hand-held vibration tools (Bovenzi, 2006). Motivated by preventing HAVS in the workplace, the correlation between occupational HAV exposure and HAVS has been a study of interest to industrial hygienists and ergonomists for decades. The Control of Vibration at Work Regulations 2005 created by Health and Safety Executive (HSE) of the British Government states that a daily exposure action value (EAV) of 2.5 $m/s^2$ and exposure limit value (ELV) of 5 $m/s^2$ are the highest level of HAV exposure acceptable in the workplace (HSE, 2012a). Similar regulations or guidelines exist in many jurisdictions, thus OH&S officers make worksite measurements to assess HAV exposure level and enforce the regulations, which results in large collections of HAV exposure data in each jurisdiction.

Currently, the gold standard for assessing HAV exposure is through direct field measurement using an electronic accelerometer. Although this method can accurately assess HAV, it is highly expensive and time-consuming due to the expense of hiring a measurement professional, buying measurement equipment, and frequent travel to different job sites. But there is an alternative method of assessing HAV exposure through exposure prediction modeling. Exposure prediction modeling involves statistically modeling the relationship between measured vibration and occupational characteristics which can contribute to vibration. There are two benefits of using exposure prediction modeling to assess HAV exposure in the workplace: 1) The method can be highly useful for future epidemiological studies involving HAVS; 2) it can define which occupational characteristics are most powerful in predicting HAV exposure thereby identifying avenues for intervention. In most epidemiological exposure-response studies for HAVS, questionnaires and interviews are used as time efficient means of obtaining HAV exposure information (Edlund et al., 2014; Sauni, Paakkonen, Virtema, Toppila, & Uitti, 2009; A. T. Su et al., 2013). However, studies have shown that self-reported HAV exposures can be biased and imprecise (Mason, Poole, & Young, 2011; Palmer, Haward, Griffin, Bendall, & Coggon, 2000). As an alternative, HAV exposure predictors found using exposure prediction modeling has the potential to provide more accuracy in HAV assessment than using self-reported data.

Conducting more studies to find HAV predictors using exposure prediction modeling can help confirm the significance of previously found predictors as well as find new predictors to contribute to more insights into why exposure variability exists, how large this variability is, and which factors determine differences in exposure levels among workers; these are essential knowledge for developing intervention programmes (Burdorf, 2005). The Occupational Health and Safety (OH&S) officers employed by the Ministry of Labour Relations and Workplace Safety (LRWS) in the Canadian province of Saskatchewan have amassed a large dataset of HAV measurements made during safety inspections from various industries (eg. Forestry, manufacturing, etc.), as well as information of numerous tool, worker, and worksite characteristics. Using this administrative dataset provides an opportunity to develop exposure prediction models from a readily available and inexpensive dataset to find the significant predictors of HAV exposure in the Saskatchewan workplace.

## METHODS

*Description of Data Source*

The dataset used in this study is part of a larger database from the Ministry of Labour Relations and Workplace Safety Saskatchewan, comprised of 177 vibration measurements with worker, worksite, and task characteristics collected for occupational health and safety enforcement purposes. The measured HAV is expressed as A(8) (measured in $m/s^2$), the equivalent continuous acceleration for an 8-hour workday based on root-mean-square averaging the vibration signal; this served as the dependent variable. The measurement required going to job site, attaching a tri-axial accelerometer to the tool handle and measuring vibration from three orthogonal planes: the x-plane through the back of the hand, the y-plane pass across the knuckles of the hand, and the z-plane parallel to the plane created by the metacarpal bones (shown in figure 1) (ISO, 1990). The measured vibration signal is then uploaded into a software program where A(8) is calculated.

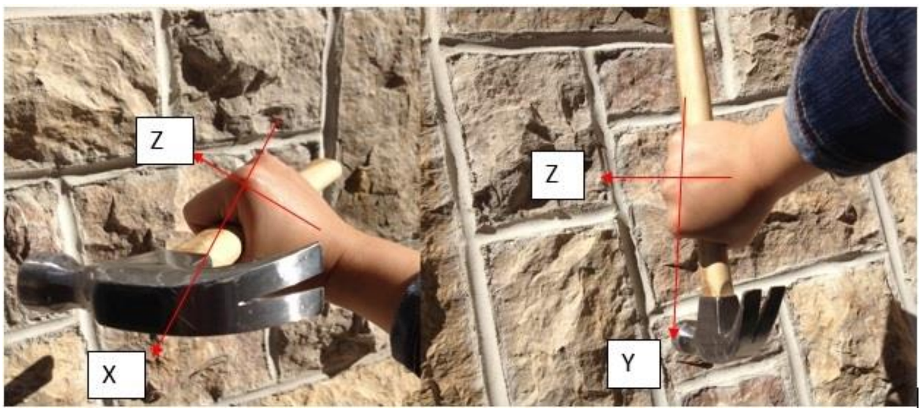


**Figure 1.** Three separate axial planes where the vibration is simultaneously using a tri-axial accelerometer.

The rest of the dataset is composed of worker characteristics (worker ID, sex, job title, height, weight, age, time on job); worksite characteristics (employer rate code (representing industries where vibration location belonged), location); measurement variables (data collector name, method of attachment, measurement date, accelerometer mounting position, accelerometer attachment method, anti-vibration control); tool characteristics (tool name (representing tool type), brand, power source, function) ;  and task characteristics (material worked on, duration of measurement).

*Data Cleaning and Model development*

As is common for administrative datasets, there were much missing data. Continuous independent variables (eg. worker age, height, etc.) were used directly and the measured HAV variable, A(8) served as the dependent variable. Linear regression modeling analysis was performed with STATA 13 (Statacorp, College Station, United States), generalized estimating equations (GEE) analysis with SPSS (IBM, Armonk, United States).

Bivariate analysis using simple linear regression was performed on variables with mechanistic plausibility for a relationship with A(8) (e.g. tool type) and variables where there were reasonable contrast between categories (e.g. Worker sex was not offered because all workers were males). Variables with p-values less than 0.25 were retained for further analysis. Pearson correlation test was then applied to check for correlation between categorical variables;

variables were deemed to correlate if p-value was lower than 0.05. Some variables offered into the model had correlation with other potential predictors greater than 0.7, but nonetheless were offered to the model due to the potential of the variables to be confounders). For a list of variables eliminated due to correlation and reasons for elimination, see Appendix B(b).

Two different models to predict HAV (presented in table 1) were built. Model 1 is a comprehensive model which can be used in a future epidemiological study which involves direct measurement of HAV. Model 2 is a parsimonious model which can also be used in future epidemiological or HAV assessment studies where direct measurements will not be required. A standard model building technique was used to build the two multiple linear exposure prediction models. Multiple linear models relies on the assumption that the vibration measurements were independent, but the vibration measurements were not independent since there were more than one worker per employer and more than one vibration measurement per worker . Therefore, GEE was run for each model using SPSS to account for repeated vibration measurements.

## RESULTS

The results from table 1 show that the comprehensive model explains 27% variance of A(8) with the significant predictors. If the results of this study were used to develop a means for assessing occupational HAV exposure without the need to measure it, then the predictors will exclude accelerometer attachment method and tool brand, with the model will only explain 16% variance of A(8). The primary predictors (from both models) were power source, job type, and presence of vibration-reducing handle wrap. The results from the GEE  of both models (Appendix B (c )) yielded the same predictor coefficients of model 1, which shows that repeated A(8) measures within workers and employers did not affect the models, therefore the vibration measurements can be analyzed as independent.

## Table 1: Results Based on Bivariate and Multivariate Regression Models for Dependent Variable HAV Exposure

| Variables | Bivariate Analysis | | | Comprehensive Model (Model 1) | | | Parsimonious Model (Model 2) | | |
|---|---|---|---|---|---|---|---|---|---|
| | β | CI (95%) | P-value[1] | β | CI (95%) | P-value | β | CI (95%) | P-value |
| **Accelerometer Attachment Method (Hose clamp reference category)** | **-3.73** | **(-5.77, -1.69)** | **<0.001** | **-3.64** | **(-6.14, -1.13)** | **0.005** | - | - | - |
| **Tool power Source (pneumatic reference category)** | **-2.42** | **(-3.84, -0.997)** | **0.001** | - | - | - | - | - | - |
| Electric | - | - | - | **-3.94** | **(-7.07, -0.81)** | **0.014** | **-3.26** | **(-5.70, -0.82)** | **0.009** |
| Other | - | - | - | **-5.65** | **(-8.88, -2.41)** | **0.001** | **-4.81** | **(-7.95, -1.67)** | **0.003** |
| **Vibration control (having the wrap reference category)** | **3.25** | **(0.261, 6.24)** | **0.033** | **6.38** | **(3.39, 9.36)** | **0.000** | **5.90** | **(2.97, 8.82)** | **0.000** |
| **Job Type (Mechanic reference category)** | **-0.931** | **(-1.535, -0.327)** | **0.003** | - | - | - | - | - | - |
| Heavy Duty Mechanics | - | - | - | **0.90** | **(-2.00, 3.78)** | **0.544** | **-0.60** | **(-3.18, 1.98)** | **0.648** |
| Technician | - | - | - | **-3.46** | **(-6.85, -0.063)** | **0.046** | **-3.53** | **(-6.81, -0.25)** | **0.035** |
| Welder | - | - | - | **-3.29** | **(-6.73, 0.16)** | **0.061** | **-4.72** | **(-7.42, -2.01)** | **0.001** |
| Other | - | - | - | **-2.39** | **(-5.30, 0.52)** | **0.107** | **-3.06** | **(-5.65, -0.47)** | **0.021** |
| **Tool Brand (reference)** | **-0.337** | **(-0.835, 0.161)** | **0.184** | - | - | - | - | - | - |
| Brand 2 | - | - | - | **2.45** | **(-1.08, 5.99)** | **0.173** | - | - | - |
| Brand 3 | - | - | - | **1.72** | **(-2.41, 5.86)** | **0.411** | - | - | - |
| Brand 4 | - | - | - | **-1.83** | **(-6.49, 2.83)** | **0.439** | - | - | - |
| Brand 5 | - | - | - | **3.57** | **(-1.68, 8.83)** | **0.182** | - | - | - |
| Brand 6 | - | - | - | **0.502** | **(-2.71, 3.71)** | **0.758** | - | - | - |
| **Worker Height** | **-0.0746** | **(-0.202,0.0528)** | **0.247** | - | - | - | - | - | - |
| **Measurement Collector** | **-0.607** | **(-1.52 , 0.315)** | **0.196** | - | - | - | - | - | - |
| **Department** | **-0.883** | **(-1.77, 0.00570)** | **0.051** | - | - | - | - | - | - |
| **Industry** | 0.135 | (-0.426, 0.696) | 0.636 | - | - | - | - | - | - |
| **Accelerometer Mounting Position** | **1.30** | **(-0.220, 2.82)** | **0.093** | - | - | - | - | - | - |
| **Material worked on** | **-3.03** | **(-6.17, 0.108)** | **0.058** | - | - | - | - | - | - |
| **Worker weight** | -0.0201 | (-0.0834, 0.0432) | 0.529 | - | - | - | - | - | - |
| **Tool type** | -0.149 | (-0.751, 0.453) | 0.626 | - | - | - | - | - | - |
| **Age** | 0.0286 | (-0.0746, 0.132) | 0.583 | - | - | - | - | - | - |
| **Worker time on job** | -0.0268 | (-0.127, 0.0736) | 0.597 | - | - | - | - | - | - |
| **Measurement season** | -0.672 | (-2.20, 0.853) | 0.385 | - | - | - | - | - | - |

[1] For bivariate analysis, the significant variables with p-value <0.25 became candidate for multivariate models 1 & 2.

## DISCUSSION

### *Predictors of HAV Exposure*

A(8) from pneumatic tools were 3.94 and 5.65 $m/s^2$ higher than those with electrical and other power tools (respectively) for model 1. For model 2, A(8) from pneumatic tools were 3.26 and 4.81 $m/s^2$ higher than electrical and other power tools, respectively. The finding that pneumatic tools generate significantly higher HAV than other energy sources is similar to the results of other studies which compared difference of vibration emitted by pneumatic and tools of other power sources (Phillips et al., 2007). This could be caused by pneumatic tools being run on compressed air that creates a sudden burst of energy when air restores its original volume. Conversely, electricity which is more constant and gives lower revolutions per minute (RPM), air pressure (psi) and horsepower. In this dataset, pneumatic tools were the dominant category for tool power source (composed of 72% of tool power source variable, 18% for electric and 10% for other), therefore, it is possible that there were more representations of higher A(8) with pneumatic tools. The tool power source in this study effectively acts as a surrogate for the mechanical power provided by the tools for different tasks because specific tools were chosen to perform specific tasks during data collection.

Vibration control was a binary (have or have not) consistent predictor for both models. Without handle wrap, the vibration was 5.90 – 6.38 $m/s^2$ higher than with handle wrap isolating ~83% (1 - 1/5.9) of vibration. The handle wrap was made of sheets of cut up Sorbothane (a highly damped, viso-elastic polymeric solid that flows like a liquid under load) fitted to the tool handle. This shows that having handle wraps can help significantly isolate emitted vibration from reaching the workers' hands. Similar studies have yielded the same results; handle wrap has been shown to reduce up to 85.6% of vibration in other studies as well (Dale et al., 2011; Milosevic & McConville, 2012). Hence, in the future, it would be wise to continue to encourage workers to use handle wrap with handheld vibration tools. Also, having or not having handle wrap during work task will be an important question when assessing HAV exposure in future research.

For model 1, the only job category that showed significant relationship to HAV exposure were technicians, which shows that technicians had 3.46 $m/s^2$ lower A(8) than mechanics. For model 2, the result was technician, welder, and other categories had 3.53, 4.72, and 3.06 $m/s^2$ lower A(8) than mechanics. In the context of this study, workers in the mechanic category often performed production and maintenance work. It is probable that mechanics require the use of vibration tools more than technicians because mechanics' job involves repairing metal structures using forceful tools, while technicians' job involves testing and diagnosing problems. It is also probable that the nature of work performed by mechanics required more forceful actions with tools, which required high vibration emission and required firmer grip for tool control, thereby leading to higher A(8) than technicians and other job categories. A study of welder HAV exposure shows that welders' exposure to vibration decreased from 3.9 $m/s^2$ to 1.9 $m/s^2$ between 1987 to 2008 has (Burstrom et al., 2010). Since the measurements from the current study were taken more recently, the welders exhibited lower HAV, perhaps influenced by this decrease of vibration. Having three categories within job type shown as significant for predicting A(8) is an indication that job type is a significant predictor for A(8). This is a novel result, since to our knowledge no study has found job type as a significant predictor for HAV.

Tool brand and accelerometer attachment methods were excluded from model 2 because it is meant to be used when vibration measurement was not involved. For model 1, the tool brand was found to be a confounder which correlates with A(8) as well as all significant predictors except job type. Correlation of brand with A(8) shows, for this dataset, vibration emissions are different between different brands. For the brand's correlation with accelerometer attachment method, it could be due to hose-clamp being the more dominant category in the accelerometer attachment method variable, which lead to more brands being tested through hose clamp than T-bar. Also for this dataset, brand had a correlation with vibration control (a variable where "not having vibration control" is the dominant category), which led to a correlation with brand. The accelerometer attachment method's reference category was using hose clamp to attach accelerometer to the tool. T-Bar attachment method used to attach accelerometer to tool gives a 3.64 $m/s^2$ lower A(8) than a measurement done by hose clamp. On consultation with the occupational health and safety officers responsible for collecting this data, we learned that hose clamp is the preferred method attaching accelerometer due to its reputation for stability and more accurate vibration measurements.

**Figure 2:** Hose clamp (left) and T-bar (right) are two methods of attaching accelerometer

Worker characteristics were not found to be significant in either model developed in this study. The worker characteristic variables were divided as worker age, height, weight, and time on job, and were all found to be insignificant at the bivariate level. The result is similar to the result of one study found in the systematic review, where the worker variables were represented as multiple variables (eg. Age, body height, length and volume of hands, etc.) with none of them were found as significant (Liljelind et al., 2013). Also, for significant predictors such as job type and tool power source, the confidence intervals were quite wide due to small sample size, suggesting that although the model parameters are significant, they are not precise.

*Utility of the Model*

The percentage of variance explained with the comprehensive and parsimonious models, 27% and 19% respectively, is relatively low. A systematic review of exposure prediction modelling methods by Burstyn and Teschke (2010) found studies used to find determinants of occupational exposure (other than vibration) explained 44% to over 90% of variance in the exposures in question. The systematic review of HAV exposure prediction modeling performed by the authors of this study, found models explaining 46% (Swuste P, 1997), 58% (Liljelind et al., 2011), and 90% (Liljelind et al., 2013) of the variance in measured HAV. Sample size is not a limiting factor, since one study of 80 vibration measurements by Liljelind et al. from 2011 (lower than the 177 vibration measurements used in the present study), explained 58% of measured variance. One possible reason for low variance explained in the present study is that when studies were performed solely for the purpose of finding predictors for HAV exposure, data collection procedures were customized to accurately assess significance of predictors. For an administrative dataset, the data were not collected for the purpose for finding predictors for HAV exposure; therefore, the variables had less chances of being predictive, which could lead to a lower-performing model. Also, some variables in the dataset were excluded from the model early on because there were not enough differences between variable categories to give significance to these variables.

Due to the low variance level explained by the models, it is not sensible for these to be the sole method used to assess hand-arm vibration exposure. But the significant predictors of this model can be taken into consideration in the future for protection research and safety precaution installation purposes. Both models included three predictors: job type, vibration control, and tool power source. In future studies where HAV exposure is assessed for large numbers of workers, these three predictors can become three areas where information can be more thoroughly collected. A research survey made with these changes can provide a better assessment of vibration than a survey created with questions without any basis in HAV measurement. The 73% variance not explained by this model could be due to missing relevant variables. Variables identified as significant predictors in previous studies include tool characteristics such as tool age, tool weight, operating power, and material worked on (Coggins et al., 2010; Dewangan & Tewari, 2009; Swuste P, 1997). These tool characteristics were either not collected for the administrative dataset because they did not serve the Labour Ministry's purpose or, as in the case of material worked on, the category was too homogeneous to contribute to the variance explanation. In the future, these variables can be collected in the administrative data to help better assess HAV exposure.

*Strengths and Limitations: Considerations for Administrative Data*

This study contributes to the growing area of exposure prediction modeling of HAV with occupational characteristics. As the first study to use administrative data, it gives insights into the usability of administrative data for assessing HAV as well as contribute confirming the significant predictors found in previous studies and finding novel HAV predictors. The strength and limitations of this study stems from the same place – the administrative dataset. For instance, the dataset used here had 177 HAV measurements but only 79 data for certain variables (eg. worker age, height, etc.) The missing data also could have made the categories of certain variables uneven, which led to the variable being tested as insignificant while in a scenario where the missing data were less, the variable might have been significant. This phenomenon can be further exacerbated by how recoding was done for this dataset. For experimental research data were carefully collected for research purposes, data are easy to recode because definitions are documented and standard language is used. The language used while collecting administrative data is far more varied and assumptions had to be made when recoding the categorical variables, which could lead to misclassification and bias towards the null. The generalizability of the data should also be carefully considered. Although this study is unique in presenting a wide variety of industries, job titles, worksites, and tools, it may not be representative of typical worksites. The data were collected when occupational health and safety officers were assigned or called to inspect vibration exposure levels, not randomly; therefore the measurements may reflect higher than average exposures.

## CONCLUSION

The results of this study show that tool power source, job type, vibration control, tool brand, and accelerometer attachment method are significant predictors of HAV exposure measured in real worksites. The predictors were able to explain 27% of the vibration variance. The results show that administrative data can be used to find the predictors of HAV exposure, but the predictors only explain a low percentage of variance; this is possibly due to the difficulty of accurately classifying categorical variables in administrative datasets and the limited number of useful variables in the dataset compared to experimental research datasets. In the future, a larger dataset with more detailed collected data is needed to generate a more generalizable and robust model. Also, it is important to use standard language when collecting categorical variable data to ensure that each category is easily recognizable for categorization and analysis. There are some variables mentioned in previous studies but not tested in this study (eg. Tool weight, tool age, etc.) that could be important in influencing hand-arm vibration exposure; if the information of those variables can also be collected, it could mean a better assessment of HAV exposure.

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## Chapter 4: Discussion

### *Findings of the Systematic Review*

Exposure prediction modeling of workplace HAV exposure is a relatively new area with few studies devoted to it. Before the systematic review presented in this thesis (see chapter 2), there were no known reviews conducted specifically to modeling HAV exposure using occupational characteristics. Despite the small number of relevant studies found, they did provide information on what types of studies were performed, what type of models were developed, what types of predictors were found significant by the models, and (for some studies) how much HAV variance was explained by the significant predictors.

The review included three types of studies: experimental, quasi-experimental and observational studies. Most simulated studies involving few selected participants were experimental and quasi-experimental, unlike observational studies where the HAV exposure was collected during real work situations. This is probably due to the fact that it was easier to maintain controlled conditions and took less time to use simulations compared to real work conditions. Two studies involved multiple linear regressions, one involved multiple logistic regression, and the rest used ANOVA. The studies investigated tool predictors more often than other types of predictors; the significant predictors found among the studies include tool characteristics such as tool brand, tool age, tool weight, material worked on, and tool type. Worker variables were found to be significant only when 'participant' was tested as one single predictor, not as individual worker characteristics (eg. Worker height, weight, etc.). Three studies reported percentage of variance explained by each variable: tool variables (18 - ~50%) (Liljelind et al., 2013; Swuste et al., 1997) were the most dominant while the interaction variable of tool with participant (12%)(Liljelind et al., 2011) , showing that participant characteristics also influence the HAV exposure.

*Summary of exposure prediction modeling study results and its relation with systematic review results*

The exposure prediction modeling study (see chapter 2) used occupational health and safety administrative data obtained from the Ministry of Labour Relations and Workplace Safety to model HAV using occupational characteristics. In the two models generated, five significant predictors were found: 'tool brand', 'tool power source', 'accelerometer attachment method', 'job type', and 'vibration control by handle wrap'. The comprehensive model explained 27% of A(8) variance with all five variables, and the parsimonious model predicted 16% of A(8) variance after removing the variables 'tool brand' and 'accelerometer attachment method'. With both models, the HAV measurement A(8) was used as a dependent variable, which is not a health-based outcome. However, A(8) is an exposure related to the development of HAVS, which is a health outcome. Since addressing HAVS will require mitigating HAV, understanding HAV exposure is a necessary step.

Unlike the results of the systematic review, tool characteristics did not dominate the prediction models; the predictors consistently found in the models presented here were: 'tool power source', 'job type', and 'vibration control by handle wrap'. The results showed that pneumatic tools produced 3.26 – 3.94 $m/s^2$ more vibration than an electrical tool, and 4.81 – 5.65 $m/s^2$ more vibration of other types of tools in the study. For tools without handle wrap, the vibration measured was ~84% higher than tools with handle wrap. For 'job type', technicians had 3.46 – 3.53 $m/s^2$ less vibration than mechanics for both models; for the parsimonious model, it was shown that welders and other job types (besides technician, heavy duty mechanics, and mechanics) in the study were exposed to 4.72 and 3.06 $m/s^2$ less vibration than mechanics respectively. 'Tool brand' was an important confounder, which correlated with A(8) as well as all significant predictors except 'job type'. The 'accelerometer attachment method' showed that the A(8) was 3.64 $m/s^2$ lower for T-bar than for hose clamp, which gave the suggestion that hose clamp can generate higher accuracy of A(8) measurement. This was confirmed by occupational health and safety officers who performed the measurements.

The results from the modeling study shows that in this dataset, workers who work with tools of certain power sources (eg. Pneumatic) in certain professions (eg. Mechanics), are more likely to receive higher vibration levels than others (eg. A technician working with electric tools). Having a protective measure (eg. A handle wrap) can also significantly reduce HAV exposure. 'Tool power source' being a significant predictor confirms results of the systematic review where tool characteristics were shown to contribute significantly to HAV exposure. The significance of 'job type" offers a different perspective because it was a predictor considered in this study but was not considered as a potential predictor in the studies found in the systematic review. The significance of 'vibration control by handle wrap' was expected due to previous non-modeling studies (found outside the systematic review) showing decreases in vibration when used (Dale et al., 2011; Welcome et al., 2004). 'Tool brand' was found as a significant predictor in the systematic review, while in the modeling study tool brand was shown as confounder. This is an indication that 'tool brand' could be a significant predictor for HAV, but was not identified here due to missing data and the lack of representation in some categories of the categorical variables in the administrative dataset. The significant predictors found in the modeling study confirmed the significance of predictors found in the systematic review as well as contributed new predictors into the arena of possible HAV predictors.

*Applications and implications for practice and research*

The results presented in this thesis can be used for HAVS research and prevention. The path of HAVS research and prevention involves four steps: 1) Injury surveillance (estimate the extent and nature of HAVS), 2) Exposure assessment (determining the patterns of exposure), 3) Epidemiology (describing relationship between exposure and HAVS) and 4) Interventions (developing and evaluating strategies to decrease exposure and preserve health). The research described in this thesis primarily belongs to the exposure assessment category. However, by providing a cheaper method of assessing HAV exposure in the workplace in lieu of the expensive direct measurement method, the findings presented here can also contribute to the other three steps in the path of researching and preventing HAVS.

Surveillance involves estimating the extent of HAVS in the population and keeping track of its level and impact. HAVS is a highly difficult disease to track. Although the source of the disease is known to be HAV exposure, an objective medical test for HAVS does not exist. Certain types of workers known to use hand-held vibration tools for long periods of time (eg. Miners and construction workers) may be transient workers, which means they are difficult to track. Also, due to the cumulative nature of vibration in the hand and arm, it is possible for workers to develop HAVS symptoms many years after leaving their jobs, making it difficult to trace their HAVS to their jobs. The significant predictors found in the modeling study and the systematic review can potentially aid the surveillance of HAVS through identifying a target high-HAVS-risk population. For example, workers who used pneumatic tools, who were mechanics, and had weak or no vibration control protection while working can be observed more carefully for signs of developing HAVS.  Having an estimate of a population of people with factors which makes them most exposed to HAV gives a rough idea on how many people will likely develop, are developing, or have already developed HAVS. This will be helpful for future HAVS studies where epidemiologists can study the target population in order to find a more precise distribution of HAVS and have an easier access to HAVS patients to study the nature of the disease.

As for exposure assessment methodology of HAV, two extreme methods have been described and tested for accuracy in the literature: the direct measurement and self-reporting methods. Self-reporting has been used in several HAVS epidemiological studies to estimate the amount of HAV exposure (Sauni et al., 2009; A. T. Su et al., 2013; T. A. Su, Hoe, Masilamani, & Awang Mahmud, 2011), but it has been shown to be highly imprecise when compared with measured vibration (McCallig, Paddan, Van Lente, Moore, & Coggins, 2010). With exposure prediction modeling, the significant predictors found are the areas where information can be collected to assess HAV. While still not as accurate as direct measurement, it can be more accurate than self-reported estimates of vibration level. For the significant predictors found in the modeling study, information on the significant predictors (the source of power of the tools used, the person’s job type, whether or not the person has been wearing protective gloves, etc.) can be collected using a survey to estimate HAV exposure. Although this method of collecting HAV exposure information is not as precise as direct measurement, it can be more quickly obtained, with less cost, and for more individuals.

In terms of the epidemiology of HAVS, it is known that HAVS is caused by hand exposure to vibration, and the degree of the vibration exposure influences the resultant degrees of HAVS (Miyashita, Shiomi, Itoh, Kasamatsu, & Iwata, 1983). The HAV has been shown to be influenced by multiple tool characteristics (eg. 'Tool type' (Vergara et al., 2008), 'tool power source'(Phillips et al., 2007)) and worker characteristics (eg. 'worker grip strength' and 'hand diameter' (Welcome et al., 2004)) along with many others found in the systematic review and the modeling study.

In terms of prevention strategies, knowing which factors increase or decrease vibration can help target opportunities for intervention. The significant predictors found in both the systematic review and modeling study points towards target populations where safety precautions can be applied most extensively to install the most economical protection. The fact that participant characteristics were not as frequently significant in the studies compared to tool characteristics shows that changing worker characteristics is likely a less fruitful venue for decreasing the impact of HAV exposure.  It is more effective and practical to control non-worker characteristics (eg. tool characteristics, handle wrap) such as providing regular tool maintenance and providing workers with tool handle wrap or anti-vibration gloves to those who receive the most HAV exposure (eg. Mechanics). For example, the results of chapter 3 showed that welders received lower vibration exposure compared to heavy duty mechanics. In a situation where a limited prevention budget must be allocated to different work groups, it would be wise in that case to invest protective measures in heavy duty mechanics rather than welders due to their higher vibration exposure.

*Methodological considerations: systematic review*

The search algorithm developed for the systematic review was broad for the purpose of casting a wide net to maximize detection of relevant studies. Despite long-time recognition of HAVS as an important health concern, it was challenging to identify specific search terms to identify relevant articles; comprehensive sets of search terms such as 'occupational disease' and 'ANOVA' were included as search terms (see appendix A for a full listing of search terms). Therefore, it is highly unlikely that a relevant study was missed during the search process.

The relevance of the articles found through the search algorithm was rigorously assessed by applying five binary questions at title, abstract, and full text levels of the study by two independent reviewers. This method ensured that only relevant studies were kept for data extraction. A large amount of studies were discarded at the title level. It is very common in the scientific literature that the title of an article does not reflect what went on during the study; therefore, it is possible that the title misled the screener into discarding it early. Ideally, the screening should be performed by looking through the full text of every article found by the search algorithm where a more thorough understanding of the study would allow screeners to make better judgments to keep it or not. Unfortunately, this method is time consuming. This means although the screening method can ensure screening is completed quickly as well as ensure all articles kept in the end were relevant, it is possible there could be a few articles missed during the process.

*Methodological considerations: exposure prediction modeling*

Chapter 3 used exposure prediction modeling to identify significant HAV predictors from an administrative dataset that had been collected over a long period of time to inexpensively test HAV predictors. Although two models were successfully built with standard model building techniques using the administrative data, imperfections in the administrative dataset and the model building method could decrease the robustness of the models.

There are several downsides to administrative data: administrative data may not always meet the analytical requirements suitable to the research endeavor since it was not collected for research purposes; administrative data may not be as accurate as survey data because it often does not go through the same rigorous protocol design steps and it is often difficult to contact the originators of the data; a standard sampling scheme may not be adhered to by the data collectors, thereby introducing biases; and access to administrative data is often not timely, since significant time may pass between time of data collection and accessing the data. The worksite vibration dataset used for the exposure prediction modeling study had some of the same issues as all administrative data. In addition, the dataset size was 177 measurements, which is quite small compare to administrative datasets of thousands or hundreds of thousands of observations. Nevertheless, the data did meet the analytical requirements of this study.

Imperfections of the exposure prediction modeling study using administrative data mainly came from the nature of administrative data when used in research analysis. A standardized or stratified sampling scheme was not adhered to during data collection, which may also have led to categories of certain categorical variables (eg. Material worked on and sex) with low numbers in certain categories. Hence, the categorical variables ‘material worked on’ and ‘sex’ were eliminated early on due to under-populated categories and inability to test for their significance. Therefore, in the future, when it is observed that a categorical variable cannot be included in a model due to underrepresentation of certain categories, it may be beneficial to focus data collection in a stratified or quasi-experimental way to populate the less-represented category before analyzing the dataset. Collecting occupational health and safety worksite measurements randomly and more frequently could lead to HAV exposure assessment in the future. However, there are tradeoffs in changing the sampling strategy. Collecting solely random data for HAV assessment may delay the finding of high HAV exposure in certain workplaces, and collecting data solely based on suspicion of high HAV exposure will yield higher HAV exposure estimates higher and more difficult to generalize (as with the data used for this study). Ideally, futureexposure data should be collected in a more randomized fashion in addition to data collection based on suspicion of excessive vibration exposure. In addition, a few continuous variables (ex. Worker age, height, weight, etc.) were missing data for more than half the cases. Despite the missing data, there were sufficient data for the bivariate analysis. Although the continuous variables were mostly eliminated at the bivariate level and none of them were shown to be significant in the multivariate model (a result consistent with significant predictors found in systematic review), having a full set of data for the continuous variables would have provided a stronger evidence for the consistency of the results. Another issue with the dataset is the language used to fill the dataset was not standard. The categorical variables (eg. job title) were divided into categories based on the definition of the terms used for the data; but when a dataset is without a standard language or coding scheme for the collected data, it is easy to make mistakes during categorization or for many data to be categorized as ‘unknown’ or ‘other’. Therefore, when collecting HAV administrative data in the future, it would be beneficial if categorical data were collected with standard, consistent language so different categories can be easily recognized.

The exposure prediction models were built using a standard method of model building, a method that is prone to over-fitting (Hosmer, Lemeshow, & Sturdivant, 2013) – including variables which do not truly have significance in influencing HAV. The variables included in the model due to over-fitting could lead to confusion when attempting to implement the results of the modeling study in a workplace, eventually lead to overspending of limited funds in unnecessary places. Despite risk of over-fitting, there were some consistencies between the predictors found in the models and those found through systematic review, which shows that it is unlikely that they are in the model due to over-fitting. For the purpose of research, since we are in a stage of attempting to find new predictors for HAV, identifying new predictors (whether as a result of over-fitting or not) will allow their significance to be tested further in the future.

The study models built in chapter 3 were multiple linear regression models, similar to the models found during systematic review. However, for a multiple linear regression model to be built, each potential predictor must be independent from each other. This dataset contains the variable employer, employee, and A(8) (measured from each employee). For each employer, more than one employee was measured and from each employee, more than one A(8) measurement was taken; therefore, the potential predictors were not independent. To address this, GEE was run for both multiple linear models because GEE can account for the dependence between employer, employee, and A(8). The parameters of the GEE models were nearly identical to the multiple linear regression models, therefore, the dependence among the three variables did not affect the models. The models were not validated due to the difficulty of obtaining a suitable model validating set, but a proper method of validating this model would be to find a similar dataset (which employed the same collection methods) and apply the models to them to predict and check for residuals and for imprecision and bias between predicted and measured A(8) values (Bland & Altman, 2010).

*Considerations for future research*

Results of the research presented here can contribute to this field by informing future studies, both literature reviews and modeling studies. For studies found in the systematic review, differences between participants were used as a single vague predictor without explaining what the specific differences were between the participants. In one reviewed study, the authors stated that the difference of HAV exposure between participants could be caused by the differences between hand grip applied among the participants, although hand grip strength was not used as a separate variable (Dewangan & Tewari, 2009). It would be interesting in future studies to test individual characteristics of the participants suspected to contribute to higher HAV exposure specifically rather than grouping them into a single ‘participant’ variable; differences in hand grip applied among the participants along with work experience, worker age, and sex could be considered. More studies performed in the area of exposure prediction modeling of occupational

HAV, along with HAVS being more recognized as an occupational disease will encourage more precise keywords to be developed for searching for these studies, thereby making them easier to access.

Since standard model building method is one with high risk of over-fitting (having too many parameters relative to number of observations), finding better model building methods for HAV exposure will allow more robust models to be built with more accurate predictors found. The bootstrap method has been successfully used to develop more robust risk prediction models than standard methods with lower risk of over-fitting (Billah, Reid, Shardey, & Smith, 2010), and could be explored for HAV exposure in the future. The method involves dividing the dataset in half into a model building set and model validation set, where 1000 bootstrap samples can be selected with replacement. The potential significant predictors will be selected from the 1000 bootstrap models generated from the 1000 bootstrap samples and the most robust model would be selected from each model built with significant predictors (found in at least 60%, 70%, 80%, … of bootstrap models). A robust model building method needs to be coupled with a strong dataset to produce an accurate model. Model validation is also a good avenue for future research. Although it is possible that the models can be validated using a different dataset, in this study validation was not feasible because the small size of the dataset. The dataset used for the modeling study will increase in size as more data will be collected in the future and making it suitable for validation.

*Conclusion*

The systematic review presented in chapter 2 is the first published systematic review for studies involving exposure prediction modeling of HAV. Based on the few studies found in the literature, it is clear that exposure prediction modeling of HAV has not been studied extensively. Several different styles of study has been performed and most of the significant predictors were tool-related factors. The HAV prediction models were mostly multiple linear models, capable of explaining from 46 – 90% of HAV variance. Therefore, tool-based characteristics should be considered when developing exposure-prediction models.

The HAV exposure prediction model using administrative data was an attempt to overcome the time and cost issues of assessing HAV exposure. The main aim of the study was to develop statistical models which can be used to find significant predictors of HAV in the workplace which can be used to assess occupational HAV exposure. There were difficulties working with this administrative dataset due to missing data, non-random data collection, the lack of difference within certain categorical variables and difficulties of obtaining additional data. Nevertheless, the two models generated from the study found five predictors for A(8), and predicted 16 - 27% of measured HAV variance. Along with the predictors found in the systematic review, the predictors found in the models can be used in the future for efficiently installing safety measures and help develop evidence-based survey items to assess exposure in large epidemiological studies. This study contributes to a small but growing body of research on exposure prediction modeling of HAV, while using different sources of data.

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## APPENDIX A: Systematic Review Protocol

## A(a): Search Terms

**Medline**

| **"Occupational diseases" search terms** | **# of articles** | **"Hand-arm vibration" search terms** | **# of articles** | **"Exposure modelling" search terms** | **# of articles** |
|---|---|---|---|---|---|
| 1. exp Occupational Medicine/ | 21723 | 10. exp Vibration/ **and** (exp Hand Deformities, Acquired/ or exp Hand/ or exp Hand Bones/ or exp Hand Injuries/ or exp Hand Joints/ or arm/ or elbow/ or forearm/ or forearm injuries/ or humeral fractures/ or wrist injuries/ or radial artery/ or ulnar artery/ or exp radial nerve/ or exp ulnar nerve/) | 1848 | 13. (determin* adj4 expos*) .ab,ti.. | 10082 |
| 2. exp Occupational Diseases/ | 105732 | 11. ((hand* or arm*) adj2 vibrat*).ab,ti. | 757 | 14. statistic* model*.mp. or exp Models, Statistical/ | 285345 |
| 3. exp Occupational Exposure/ | 49881 | 12. hand-arm vibration syndrome.mp. or exp Hand-Arm Vibration Syndrome/ | 362 | 15.( expos* adj4 predict*).ab,ti. | 3529 |
| 4. (occupat* adj3 expos*).ab,ti. | 18605 | | | 16. (assess* adj4 expos*).ab,ti. | 15509 |
| 5. (occupat* adj3 hazard*).ab,ti. | 3007 | | | 17. predictive value of tests.mp. or exp "Predictive Value of Tests"/ | 142660 |
| 6. (work* adj3 expos*).ab,ti. | 19301 | | | 18. regress* analy*.mp. or exp Regression Analysis/ | 385196 |
| 7. exp Occupational Health/ | 24636 | | | 19. risk adj 5 assess*.mp. or risk assessment/ | 222354 |

| | | | | | |
|---|---|---|---|---|---|
| 8. exp ergonomics/ | 44749 | | | 20.exp Algorithms/ | 212236 |
| 9. exp environmental monitoring/ | 76454 | | | | |
| 21. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 | | | 297941 | | |
| 22. 10 or 11 or 12 | | | 1467 | | |
| 23. 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 | | | 967477 | | |
| 24. 21 and 22 and 23 | | | 149 | | |

## Scopus

| | | |
|---|---|---|
| **"occupational exposure" search terms** | (TITLE-ABS-KEY(occupat* medicine)) OR (TITLE-ABS-KEY(occupat* disease*)) OR (TITLE-ABS-KEY(occupat* W/3 expos*)) OR (TITLE-ABS-KEY(occupat* W/3 hazard*)) OR (TITLE-ABS-KEY(occupat* health)) OR (TITLE-ABS-KEY(work* W/3 expos*)) OR (TITLE-ABS-KEY(ergonomic*)) OR (TITLE-ABS-KEY(environ* monitor*)) | 543,895 |
| **" hand-arm vibration" search terms** | (TITLE-ABS-KEY(hand* W/2 vibrat*)) OR (TITLE-ABS-KEY(arm* W/2 vibrat*)) OR (TITLE-ABS-KEY(wrist* W/2 vibrat*)) OR (TITLE-ABS-KEY(forearm* W/2 vibrat*)) OR (TITLE-ABS-KEY(humer* W/2 vibrat*)) OR (TITLE-ABS-KEY(finger joint* W/2 vibrat*)) OR (TITLE-ABS-KEY(hand joint* W/2 vibrat*)) OR (TITLE-ABS-KEY(wrist joint* W/2 vibrat*)) OR (TITLE-ABS-KEY(carpal bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(metacarpal bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(arm bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(humer* bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(radial artery W/2 vibrat*)) OR (TITLE-ABS-KEY(ulnar artery W/2 vibrat*)) OR (TITLE-ABS-KEY(radial nerve W/2 vibrat*)) OR (TITLE-ABS-KEY(ulnar nerve W/2 vibrat*)) | 3583 |
| **"Modeling methodology" search terms** | (TITLE-ABS-KEY(expos* W/4 predict*)) OR (TITLE-ABS-KEY(assess* W/4 expos*)) OR (TITLE-ABS-KEY(determin* W/4 expos*)) OR (TITLE-ABS-KEY(predict* W/2 test*)) OR (TITLE-ABS-KEY(Statistic* model*)) OR (TITLE-ABS-KEY(regress* analy*)) OR (TITLE-ABS-KEY(risk W/5 assess*)) OR (TITLE-ABS-KEY(algorithm*)) | 2,197,860 |
| **1 and 2 and 3** | ((TITLE-ABS-KEY(occupat* medicine)) OR (TITLE-ABS-KEY(occupat* disease*)) OR (TITLE-ABS-KEY(occupat* W/3 expos*)) OR (TITLE-ABS-KEY(occupat* W/3 hazard*)) OR (TITLE-ABS-KEY(occupat* health)) OR (TITLE-ABS-KEY(work* W/3 expos*)) OR (TITLE-ABS-KEY(ergonomic*)) OR (TITLE-ABS-KEY(environ* monitor*))) AND ((TITLE-ABS-KEY(hand* W/2 vibrat*)) OR (TITLE-ABS-KEY(arm* W/2 vibrat*)) OR (TITLE-ABS-KEY(wrist* W/2 vibrat*)) OR (TITLE-ABS-KEY(forearm* W/2 vibrat*)) OR (TITLE-ABS-KEY(humer* W/2 vibrat*)) OR (TITLE-ABS-KEY(finger joint* W/2 vibrat*)) OR (TITLE-ABS-KEY(hand joint* W/2 | 275 |

| | | |
|---|---|---|
| | vibrat*)) OR (TITLE-ABS-KEY(wrist joint* W/2 vibrat*)) OR (TITLE-ABS-KEY(carpal bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(metacarpal bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(arm bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(humer* bone* W/2 vibrat*)) OR (TITLE-ABS-KEY(radial artery W/2 vibrat*)) OR (TITLE-ABS-KEY(ulnar artery W/2 vibrat*)) OR (TITLE-ABS-KEY(radial nerve W/2 vibrat*)) OR (TITLE-ABS-KEY(ulnar nerve W/2 vibrat*))) AND ((TITLE-ABS-KEY(expos* W/4 predict*)) OR (TITLE-ABS-KEY(assess* W/4 expos*)) OR (TITLE-ABS-KEY(determin* W/4 expos*)) OR (TITLE-ABS-KEY(predict* W/2 test*)) OR (TITLE-ABS-KEY(Statistic* model*)) OR (TITLE-ABS-KEY(regress*analy*)) OR (TITLE-ABS-KEY(risk W/5 assess*)) OR (TITLE-ABS-KEY(algorithm*))) | |

**<u>CINAHL</u>**

| **“occupational exposure” search terms** | **# of articles** | **“ hand-arm vibration” search terms** | **# of article s** | **“Modeling methodology” search terms** | **# of article s** |
|---|---|---|---|---|---|
| 1. MH "Occupational Exposure” | 12134 | 11. (TI (hand* OR arm*) N2 vibrat*) OR (AB (hand* OR arm*) N2 vibrat*) | 94 | 15. (MH "Models, Statistical") | 14788 |
| 2. TI occupat* N3 expos* OR AB occupat* N3 expos* | 427 | 12. (MH "Vibration") | 2076 | 16.TI statistic* model* OR AB statistic* model* | 32 |
| 3. (MH "Occupational Diseases”) | 7046 | 13. (MH "Hand+") OR (MH "Fingers+") OR (MH "Wrist") OR (MH "Forearm") OR (MH "Elbow") OR (MH "Arm") OR (MH "Finger Joint") OR (MH "Carpal Joints") OR (MH "Hand Joints+") OR (MH "Carpometacarpal Joints") OR (MH "Metacarpophalangeal Joint") OR (MH "Wrist Joint") OR (MH "Carpal Bones") OR (MH "Metacarpal Bones") OR (MH "Arm Bones") OR (MH "Humerus") OR (MH "Radius") OR (MH "Ulna") OR (MH "Radial Artery") OR (MH "Ulnar Artery") OR (MH "Radial Nerve") OR (MH "Ulnar Nerve") OR (MH "Median Nerve") OR (MH "Hand Deformities, Acquired+") OR (MH "Arm Injuries+") | 27585 | 17. TI determin* N4 expos* OR AB determin* N4 expos* | 953 |

| | | | | | |
|---|---|---|---|---|---|
| 4. (MH "Occupational Medicine”) | 128 | 14. 12 and 13 | 62 | 18. TI expos* N4 predict* OR AB expos* N4 predict* | 21 |
| 5. (MH "Occupational Hazards+ ") | 6214 | | | 19. TI assess* N4 expos* OR AB assess* N4 expos* | 2119 |
| 6. TI occupat* N3 hazard* OR AB occupat* N3 hazard* | 42 | | | 20. (MH “risk assessment”) | 45716 |
| 7. TI work* N3 expos*OR AB work* N3 expos* | 15398 | | | 21. TI risk N5 assess* OR AB risk N5 assess* | 1248 |
| 8. (MH "Ergonomics+”) | 253 | | | 22. MH predictive value of tests | 25,775 |
| 9. (MH "Occupational Health+") | 34,606 | | | 23. (MH "Predictive Validity") OR (MH "Predictive Research") | 4,367 |
| 10. (MH "Environmental Monitoring") | 3002 | | | 24. (MH "Regression+") | 156,560 |
| | | | | 25. TI regress* analy* OR AB regress* analy* | 101 |
| | | | | 26. MH “Algorithms” | 16125 |
| | | | | | |
| | | | | | |
| | | | | | |
| 27. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 | | | 62,909 | | |
| 28. 11 or 14 | | | 136 | | |
| 29. 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 | | | 241,837 | | |
| 30. 27 or 28 or 29 | | | 25 | | |

**Web of Science**

| **"occupational exposure" search terms** | **# of articles** | **" hand-arm vibration" search terms** | **# of articles** | **"Modeling methodology" search terms** | **# of articles** |
|---|---|---|---|---|---|
| 1. TS=(occupat* disease*) | 285,925 | 9. TS=((hand* OR arm*) NEAR/2 vibrat*) | 2022 | 13. TS=(statistic* model*) | 1,766,148 |
| 2. TS=(occupat* medicine) | 216619 | 10.TS=(vibrat*) | 446,159 | 14. TS=(determin* NEAR/4 expos*) | 43,937 |
| 3. TS=(occupat* NEAR/3 expos*) | 132,693 | 11. TS=(hand NEAR/2 injur*) OR TS=(arm* NEAR/2 injur*) OR TS=(hand bone*) OR TS=(arm bone*) OR TS=(wrist bone*) OR TS=(metacarpal bone*) OR TS=(humer* bone*) OR TS=(hand joint*) OR TS=(arm joint*) OR TS=(finger joint*) OR TS=(wrist joint*) OR TS=(elbow) OR TS=(forearm injur*) OR TS=(humer* injur*) OR TS=(wrist* injur*) OR TS=(radial arter*) OR TS=(ulnar arter*) OR TS=(radial nerve) OR TS=(ulnar nerve) | 147041 | 15.TS=(expos* NEAR/4 predict*) | 19,084 |
| 4. TS=(occupat* NEAR/3 hazard*) | 31,887 | 12. 10 and 11 | 218 | 16.TS=(expos* NEAR/4 assess*) | 85,000 |
| 5. TS=(work* NEAR/3 expos*) | 86,330 | | | 17.TS=(risk NEAR/5 assess*) | 569,124 |
| 6. TS=(occupat* health) | 33,632 | | | 18.TS=(predict* NEAR/2 test*) | 228,520 |
| 7. TS=(ergonomic*) | 30,997 | | | 19.TS=(regress* analy*) | 1,159,025 |
| 8. TS=(environ* monitor*) | 454,120 | | | 20. TS=(algorithm*) | 1038647 |
| 21. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 | | | 3,561,765 | | |
| 22. 9 or 12 | | | 4,024 | | |
| 23. 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 | | | 1,105,077 | | |
| 24. 21 and 22 and 23 | | | 447 | | |

**EMBASE**

| “Occupational diseases” search terms | # of articles | “Hand-arm vibration” search terms | # of articles | “Exposure modelling” search terms | # of articles |
|---|---|---|---|---|---|
| 1. Occupational medicine/or industrial medicine/ | 24662 | 11. vibration/ or exp high frequency oscillation/ or exp oscillation/ or exp vibration disease/ | 49524 | 16. (determin* adj4 expos*).ab,ti. | 12763 |
| 2. occupational disease/ | 83408 | 12.exp hand arm vibration/ | 123 | 17. (statistic* model*).ab,ti. or statistical model/ | 114342 |
| 3. exp occupational exposure/ | 65230 | 13. ((hand or arm) adj2 vibrat*).ab,ti. | 943 | 18. (expos* adj4 predict*).ab,ti. | 4236 |
| 4. (occupat* adj3 expos*).ab,ti. | 28267 | 14. exp hand joint/ or exp hand malformation/ or exp hand/ or exp hand injury/ or exp "bones of the arm and hand"/ or arm injury/ or elbow injury/ or wrist injury/ or exp wrist injury/ or exp radial artery/ or exp ulnar artery/ or exp ulnar artery/ or exp ulnar artery/ or exp radial nerve/ or exp ulnar nerve/ | 153568 | 19. (assess* adj4 expos*).ab,ti. | 19090 |
| 5. occupational hazard/ | 14572 | 15. 11 and 14 | 1140 | 20. predictive value/ or predictor variable/ | 52731 |
| 6. (occupat* adj3 hazard*).ab,ti. | 4096 | | | 21. exp regression analysis/ | 220937 |
| 7. (work* adj3 expos*).ab,ti. | 25966 | | | 22. risk assessment/ | 323910 |
| 8. occupational health/ | 36141 | | | 23. (risk adj5 assess*).ab,ti. | 89028 |
| 9. exp ergonomics/ | 8267 | | | 24. algorithm/ | 181919 |
| 10. exp environmental monitoring/ | 70687 | | | | |
| 25. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 | | | 219098 | | |
| 26. 12 or 13 or 15 | | | 1751 | | |
| 27. 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 | | | 740855 | | |
| 28. 25 and 26 and 27 | | | 136 | | |

**APPENDIX B: Binary Screening Questions**

**Title**

1) Did this study involve measuring hand tool vibration?
    a. If no, then discard
    b. If yes or unsure, go onto next question

**Decision guidance**:

- whole body vibration is excluded
- A lab study of hand tool vibration (even if there are no workers or 'hands' in the title, is included. (add to this on review of first articles, and after 'conflict resolution' discussion with co-reviewer)

2) Was this study done in an occupational setting or can be applied in an occupational setting?
    a. If no, then discard
    b. If yes or unsure, go onto next question

**Decision guidance:** stated specifically the types of workers and workplaces involved or that it can be applied to a real workplace setting

3) Did this study involve statistical modeling of exposure data?
    a. If no, then discard
    b. If yes or unsure, go onto next question

4) Is this article in English? (regardless of the study's country of origin)
    a. If no, then discard
    b. If yes or unsure, go onto next question

5) Did this study involve measuring vibration by vibration tools directly in the field using a tri-axial accelerometer?
    a. If no, then discard
    b. If yes or unsure, go onto next question

**Decision guidance:** we don't want self-reported or observed vibration, only direct electronic measurement

6) Did the study involve one or more of adult human data or lab-based vibration tool data?
    a. If no, then discard
    b. If yes or unsure, go onto abstract review

**Decision guidance:**

- No child subjects, no animals.

**Abstract**

1) Did this study involve measuring hand tool vibration using tri-axial accelerometer?
   a. If no, then discard
   b. If yes or unsure, go onto next question

**Decision guidance:** we don't want self-reported or observed vibration, only direct electronic measurement

2) Was this study done in an occupational setting or can be applied in an occupational setting?
   c. If no, then discard
   d. If yes or unsure, go onto next question

**Decision guidance:** stated specifically the types of workers and workplaces involved or that it can be applied to a real workplace setting

3) Did this study involve exposure predictionmodeling?
   c. If no, then discard
   d. If yes or unsure, go onto next question

**Decision guidance:** it should include the CONCEPT of exposure prediction modelling, even if it uses other terminology.

4) Is this article in English?
   a. If no, then discard
   b. If yes or unsure, go onto next question

5) Did the study involve at least one of adult human data or lab-based vibration tool data?
   a. If no, then discard
   b. If yes or unsure, go onto abstract review

**Decision guidance:** No child subjects, no animals.

**Full-text**

1) Did this study involve measuring hand tool vibration?
    a. If no, then discard
    b. If yes or unsure, go onto next question

2) Were the study data collected in an occupational setting or laboratory setting specifically for testing vibration emission of tools
    a. If no, then discard
    b. If yes or unsure, go onto next question

**Decision guidance**:

- was it stated in anywhere in article that the data was collected in an occupational setting specifically for testing vibration emission of tools?
- Was it stated anywhere in article results can be applied to estimating hand-arm vibration exposure in the occupational setting?

3) Did this study involve exposure prediction modeling?
    a. If no, then discard
    b. If yes or unsure, go onto next question

**Decision Guidance**

1. HAV should be the dependent of the estimation
2. HAV was estimated through regression analysis
    1. is stratified analysis ok - i.e. chi-square tables that show which tool is higher?
    2. must it be a continuous outcome? Is m/s2 the only unit of HAV we accept, or will we accept others?
3. modeling was specific about the difference between tools, materials, and other workplace and worker characteristics and how it contributes to HAV

4) Did this study involve measuring vibration by vibration tools directly in the field using a tri-axial accelerometer?

c. If no, then discard
d. If yes or unsure, go onto next question

**Decision guidance:** we don't want self-reported or observed vibration, only direct electronic measurement

5) Did this study involve one or more of adult human data, or lab-based vibration tool data?
   a. If no, then discard
   b. If yes or unsure, keep article

## APPENDIX C: Variables and Recoding

### C(a): Categorization of Variables

| Original Variable | Separate categories | Basis of Categories for each Variable |
|---|---|---|
| Data collector | A | By person(s) who performed measurement |
| | B | |
| | C | |
| | D | |
| Industry | A (building, construction) | By industry type |
| | B (mining and related) | |
| | C (farming) | |
| | D (manufacturing) | |
| | E (transportation & storage) | |
| | F (retail and wholesale trades) | |
| Department | Main shop | By department/location where vibration was measured |
| | Maintenance services | |
| | Production | |
| | Other* | |
| Measurement season | Cold (Jan, Feb, Dec) | By temperature range of measurement time |
| | Marginal (Mar, Apr, Oct, Nov) | |
| | Hot (May, Jun, Jul, Aug, Sept) | |
| Job title | Mechanic | By work involved |
| | Technicians | |
| | Welders | |
| | Other* | |
| | Heavy Duty Mechanics | |
| Tool type | Drill | Grouped by tool purpose (correlate with tool function) |
| | Impact Wrench | |
| | Grinder & Sanders | |
| | Hammer | |
| | Chipper & Chisel | |
| | Other* | |
| Accelerometer attachment method | Hose clamp | By attachment method name |
| | T-Bar | |
| Accelerometer attachment position | Main Handle | By attachment position |
| | Trigger handle | |
| | Other* | |
| Tool brand | Chicago Pneumatic | By brand name |
| | Ingersoll Rand | |
| | Blue point | |

| | | |
|---|---|---|
| | Mac | |
| | Makita | |
| | Other* | |
| Tool power source | Pneumatic | By source of energy |
| | Electric | |
| | Other* | |
| Anti-vibration | Yes | By having or not having anti-vibration installed during measurement |
| | No | |
| Material worked on | Metal | By metal or non-metal (because metal had a significantly higher representation than others) |
| | Other | |

## Appendix D: Variables Eliminated After Correlation Testing

| **Eliminated Variable** | **Reason** |
|---|---|
| Department of work | Correlated with all other variables, except vibration control |
| Mounting position of accelerometer | Related to accelerometer attachment method (similar because they are both related to ways of measuring vibration), had higher p-value than accelerometer attachment method during bivariate |
| Material worked on | Category had 159 entries for metal while the complete variable had 177 entries |

## APPENDIX E: Codes for Data cleaning and Modeling

C(a): SAS

```
data WORK.HAV;
   infile 'C:\Users\axl807\SAS_HAV\HAV.csv' delimiter = ',' MISSOVER DSD
lrecl=32767 firstobs=2 ;
         informat collector $50. ;
         informat industry $5. ;
         informat dept $40. ;
         informat msr_temp DATE9. ;
         informat emp best32. ;
         informat wrkr best32. ;
         informat job $40. ;
         informat age $2. ;
         informat job_time $4. ;
         informat wrkr_ht $6. ;
         informat wrkr_wt $6. ;
         informat tool $50. ;
         informat dur_msr time20.3 ;
         informat acc_att $10. ;
         informat mtpos $23. ;
         informat vib best32. ;
         informat eav $5. ;
         informat elv $4. ;
         informat notes $1. ;
         informat brand $40. ;
         informat tool_pow $20. ;
         informat vib_cont $40. ;
         informat Tool_func $32. ;
         informat photo $1. ;
         informat matwrk $40. ;
         informat sex $1. ;
         format collector $50. ;
         format industry $5. ;
         format dept $40. ;
         format msr_temp DATE9. ;
         format emp best32. ;
         format wrkr best32. ;
         format job $40. ;
         format age $2. ;
         format job_time $4. ;
         format wrkr_ht $6. ;
         format wrkr_wt $6. ;
         format tool $50. ;
         format dur_msr time20.3 ;
         format acc_att $10. ;
         format mtpos $23. ;
         format vib best12. ;
         format eav $5. ;
         format elv $4. ;
         format notes $1. ;
         format brand $40. ;
         format tool_pow $20. ;
         format vib_cont $40. ;
         format Tool_func $32. ;
```

```
         format photo $1. ;
         format matwrk $40. ;
         format sex $1. ;
input collector$ industry$ dept$ msr_temp emp wrkr job$ age$ job_time$
wrkr_ht$ wrkr_wt$ tool$ dur_msr acc_att$ mtpos$ vib eav$ elv$ notes$ brand$
tool_pow$ vib_cont$ Tool_func$ photo$ matwrk$ sex$ ;
run;

data Work.HAV;
        set HAV;
            if collector = "Aaron Unger" then collector_cat = 1;
        if collector = "Steve Bilan" then collector_cat = 2;
        if collector = "Carla Schatz" then collector_cat = 3;
        if collector = "Aaron Unger and Steve Bilan" then collector_cat = 4;
            if (industry = "B13") or (industry = "B1317") then industry_cat =
1;
            if (industry = "C6102") or (industry = "C6115")or (industry =
"C6201") or (industry = "C6208") or (industry = "C6215") or (industry =
"C6220")  then industry_cat = 2;
            if (industry = "D4108") or (industry = "D7301") then industry_cat
= 3;
            if (industry = "F2203") or (industry = "F3101") then industry_cat
= 4;
            if (industry = "G3101") or (industry = "G3103") or (industry =
"G3105") or (industry = "G5101") then industry_cat = 5;
            if (industry = "M9101") or (industry = "M9401") then industry_cat
= 6;
            if (dept = "Main Shop") or (dept = "Humboldt/Main Shop") then
dept_cat = 1;
        if (dept = "Carrot River/Maintenance") or (dept = "Automotive Shop")
or (dept = "Heavy Fleet Equipment Shop")or (dept = "Fleet Services")or (dept
= "Kindersely/Service Shop")or (dept = "Maintenance Department")or (dept =
"Maintenance Shop")or (dept = "Tisdale/Service Area")or (dept =
"Tisdale/Service Shop") then dept_cat = 2;
            if (dept = "Assembly") or (dept = "Saskatoon/Production Shop") or
(dept = "Hudson Bay/Production")or (dept = "Production")or (dept = "Welding
Shop")or (dept = "Riveting Department")or (dept = "Hudson Bay/Knife Room")
then dept_cat = 3;
          if (dept = "Condo Basement")or(dept = "Construction Site")or(dept =
"Langbank")or(dept = "Outdoors")or(dept = "Regina - Salvage")or(dept =
"Tisdale/Plasma Room")or(dept = "Transit")or(dept =
"Underground/mine")or(dept = "Wash Bay") then dept_cat = 4;
            if (msr_temp = "20FEB2013"d) or (msr_temp = "25FEB2010"d) or
(msr_temp = "26FEB2009"d) then msr_temp_cat = 1;
            if (msr_temp = "20APR2010"d) or (msr_temp = "26APR2012"d) or
(msr_temp = "27APR2010"d)or (msr_temp = "27APR2011"d)or (msr_temp =
"28APR2010"d)or(msr_temp = "29MAR2011"d)or(msr_temp =
"06OCT2009"d)or(msr_temp = "04OCT2011"d)or(msr_temp =
"05OCT2011"d)or(msr_temp = "07NOV2012"d)or(msr_temp =
"08OCT2009"d)or(msr_temp = "24NOV2011"d)or(msr_temp =
"26OCT2011"d)or(msr_temp = "27OCT2011"d)or(msr_temp =
"28NOV2012"d)or(msr_temp = "29NOV2012"d)or(msr_temp = "31OCT2011"d)then
msr_temp_cat = 2;
        if (msr_temp = "03MAY2012"d) or (msr_temp = "04JUL2012"d) or
(msr_temp = "04JUN2012"d)or (msr_temp = "05JUN2012"d)or (msr_temp =
"06JUN2012"d)or (msr_temp = "13AUG2009"d)or(msr_temp =
"15SEP2011"d)or(msr_temp = "17JUL2012"d)or(msr_temp =
```

```
"19SEP2012"d)or(msr_temp = "23JUN2010"d)or(msr_temp =
"25MAY2012"d)or(msr_temp = "29AUG2012"d)or(msr_temp = "05JUL2010"d)then
msr_temp_cat = 3;
            if (job = "Mechanic")then job_cat = 1;
            if (job = "Apprentice Heavy Duty") or (job = "Heavy Duty
Mechanic")or (job = "Journeyman Heavy Duty")then job_cat = 2;
            if (job = "Autobody Technician") or (job = "Finishing
Techincian")or (job = "Maintenance Technician")then job_cat = 3;
            if (job = "Welder") or (job = "Production Welder")or (job =
"Journeyman Welder")then job_cat = 4;
            if (job = "Assembly Worker") or (job = "Bus Driver")or (job =
"Forestry Worker")or (job = "Grinderman")or (job = "Knife Room Operator")or
(job = "Labourer")or (job = "Miner")or (job = "Plainnerman")or (job = "Plasma
Table Operator")or (job = "Pressure Washer")or (job = "Production
Worker")then job_cat = 5;
        if (acc_att = "Hose Clamp") then acc_att_cat = 1; if (acc_att = "T-
Bar")then acc_att_cat = 2;
            if (mtpos = "Anvil Body") or (mtpos = "Front Handle") or (mtpos =
"Knob Handle") or (mtpos = "Main Tool Body") or (mtpos = "Secondary Handle")
or (mtpos = "Side Handle") or (mtpos = "Steering Wheel") or (mtpos = "Top
Hand Position") or (mtpos = "Top Handle (horizontal)") then mtpos_cat = 3;
            if (mtpos = "Trigger Handle") then mtpos_cat = 2;
            if (mtpos = "Main Handle") then mtpos_cat = 1;
            if (tool_pow = "Pneumatic") then tool_pow_cat = 1;
            if (tool_pow = "Electric")or (tool_pow = "Battery") then
tool_pow_cat = 2;
            if (tool_pow = "Diesel") or (tool_pow = "Gas") or (tool_pow =
"Gas/Combustion") or (tool_pow = "Manual") or (tool_pow = "")then
tool_pow_cat = 3;
            if (matwrk = "Metal")then matwrk_cat = 1;
            if (matwrk = "Concrete")or (matwrk = "Driving on city streets")or
(matwrk = "Grass")or (matwrk = "Rock")or (matwrk = "Rubber")or (matwrk =
"Spraying water on a farm implement")or (matwrk = "Spraying water on a
truck")or (matwrk = "Wood")then matwrk_cat = 2;
            if (vib_cont = "No control in place")or (vib_cont = "Plastic
Casing")or (vib_cont = "Plastic Covered Handle")or (vib_cont = "Plastic
Handle")or (vib_cont = "Rubber Covered Handle")or (vib_cont = "Worker Wearing
Gloves")or (vib_cont = "") then vib_cont_cat = 2;
            if (vib_cont = "Handle Wrap") or (vib_cont = 'Handle Wrap - 18
months old') then vib_cont_cat = 1;
            if (tool = '1/2" Air Drill') or (tool = '1/2" Electric Drill') or
(tool = '3/8" Air Drill') or (tool = 'Angle Drill') or (tool = 'Drill') or
(tool = 'Hammer Drill') or (tool = 'Pneumatic Poly Drill')then tool_cat = 1;
            if (tool = '1" Air Impact') or (tool = 'Air Wrench') or (tool =
'1" Impact') or (tool = '1.5" Air Impact') or (tool = '1/2" Air Impact
Wrench') or (tool = '1/2" Air Wrench') or (tool = '1/2" Battery Impact
Wrench') or (tool = '1/2" Impact') or (tool = '3/4" Air Impact Wrench') or
(tool = '3/4" Impact') or (tool = '3/8" Air Impact Wrench') or (tool = '3/8"
Impact')then tool_cat = 2;
        if (tool = '1/4" Die Grinder') or (tool = '4.5" Angle Grinder') or
(tool = '4.5" Grinder') or (tool = '5" Angle Grinder')or
            (tool = '5" Grinder') or (tool = '5" Grinding wheel') or (tool =
'6" Orbital Sander') or (tool = '7" Grinder') or (tool = '9" Orbital
Sander')or
            (tool = 'Air Grinder') or (tool = 'Air Sander')or (tool = 'Angle
Grinder') or (tool = 'Cutting Grinder') or (tool = 'Die Grinder') or (tool =
'Extended Die Grinder')or
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            (tool = 'Hand Grinder') or (tool = 'Inline Sander') or (tool =
'Orbital Sander') or (tool = 'Straight Line Sander')then tool_cat = 3;
            if (tool = '1/2" Air Wrachet') or (tool = '3/8" Air Rachet') or
(tool = 'Air Buffing Tool') or (tool = 'Air Rivetter')or (tool = 'Anvil') or
(tool = 'Bead Axe') or (tool = 'Bus') or (tool = 'Descaler') or (tool =
'Eraser')or
            (tool = 'Feather Edger (Large)') or (tool = 'Feather Edger
(Small)') or (tool = 'JackLeg') or (tool = 'Plugger') or (tool = 'Pressure
Washer')or
            (tool = 'Sawzall') or (tool = 'Skiving Tool') or (tool = 'Weed
Whipper')or (tool = '7 1/4" Skill Saw ') or (tool = 'Air Powered Saw') or
(tool = 'Chainsaw')then tool_cat = 6;
            if (tool = 'Air Hammer') or (tool = 'Combihammer') or (tool =
'Jackhammer') or (tool = 'Riveting hammer') then tool_cat = 4;
            if (tool = 'Air Chipper') or (tool = 'Air Chisel')then tool_cat =
5;
            if (brand = 'Chicago Pneumatic') or (brand = 'Chicago Pneumatic
CP714')or (brand = 'Chicago Pneumatic CP721')or (brand = 'Chicago Pneumatic
CP7255')or (brand = 'Chicago Pneumatic CP749')or (brand = 'Chicago Pneumatic
CP766')or (brand = 'Chicago Pneumatic CP772H')
            or (brand = 'Chicago Pneumatic CP7733')or (brand = 'Chicago
Pneumatic CP860')or (brand = 'Chicago Pneumatic CP879') then brand_cat = 1;
            if (brand = 'Ingersoll Brand w/Snap on Chuck')or (brand =
'Ingersoll Rand')or (brand = 'Ingersoll Rand 107XPA')or (brand = 'Ingersoll
Rand 114GQC')or (brand = 'Ingersoll Rand 121')or (brand = 'Ingersoll Rand
2132G')or (brand = 'Ingersoll Rand 231C')or (brand = 'Ingersoll Rand 308A')or
(brand = 'Ingersoll Rand SFM11193') then brand_cat = 2;
            if (brand = 'Blue Point')or (brand = 'Blue Point Snap On')or
(brand = 'Bluepoint')or (brand = 'Snap On CTB4145 14.4v')or (brand = 'Snap-
On')or (brand = 'Snap-On Blue Point')or (brand = 'Snap-On IM510B')or (brand =
'Snap-On PH2050')or (brand = 'Snap-on')then brand_cat = 3;
            if (brand = 'MAC')or (brand = 'Mac')or (brand = 'Mac Tools')or
(brand = 'Mac AW6120')then brand_cat = 4;
            if (brand = '3M Model')or (brand = 'Dewalt')or (brand = 'GP')or
(brand = 'Hilti - 70')or (brand = 'Husqvarna - 365')or (brand = 'Husqvarna -
444')or (brand = 'Hutchins Pro Finisher')or (brand = 'Low Flow Flyer')or
(brand = 'MCI 437')or (brand = 'MasterCraft')or (brand = 'MasterCraft Maximum
14.4v')or (brand = 'Milwaukee')or (brand = 'Milwaukee 0-2800')or (brand =
'N/A')or (brand = 'Napa Ultra Pro')or (brand = 'New')or (brand = 'Old')or
(brand = 'Pit Pro PT 2440')or (brand = 'Power Fist')or (brand =
'Powerfist')or (brand = 'Pro Point')or (brand = 'STIHL')or (brand = 'Ultra-
Pro')or (brand = 'Westward ATM122')or (brand = '')then brand_cat = 6;
            if (brand = 'Makita')or (brand = 'Makita 5007NFA')or (brand =
'Makita 9005B')or (brand = 'Makita 9526P')or (brand = 'Makita 9527NB')or
(brand = 'Makita 9557 NB')or (brand = 'Makita GA5010')then brand_cat = 5;
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Run;

**Parameter Estimates**

| Parameter | B | Std. Error | 95% Wald Confidence Interval | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|
| | | | Lower | Upper | Wald Chi-Square | df | Sig. |
| (Intercept) | 5.560 | 2.9680 | -.257 | 11.377 | 3.509 | 1 | .061 |
| [tool_pow_cat=2] | .030 | 2.1737 | -4.230 | 4.291 | .000 | 1 | .989 |
| [tool_pow_cat=1] | 0[a] | . | . | . | . | . | . |
| [job_cat=5] | -.395 | 3.5379 | -7.329 | 6.540 | .012 | 1 | .911 |
| [job_cat=4] | -5.217 | 3.4603 | -11.999 | 1.565 | 2.273 | 1 | .132 |
| [job_cat=3] | -6.437 | 2.5446 | -11.424 | -1.450 | 6.400 | 1 | .011 |
| [job_cat=2] | -3.218 | 3.1331 | -9.359 | 2.922 | 1.055 | 1 | .304 |
| [job_cat=1] | 0[a] | . | . | . | . | . | . |
| [vib_cont_cat=2] | 1.448 | 2.4982 | -3.449 | 6.344 | .336 | 1 | .562 |
| [vib_cont_cat=1] | 0[a] | . | . | . | . | . | . |
| [brand_cat=6] | -1.212 | 2.5160 | -6.143 | 3.719 | .232 | 1 | .630 |
| [brand_cat=5] | .327 | 3.3286 | -6.197 | 6.850 | .010 | 1 | .922 |
| [brand_cat=4] | .022 | 3.8792 | -7.581 | 7.625 | .000 | 1 | .996 |
| [brand_cat=3] | -2.728 | 2.4011 | -7.434 | 1.978 | 1.291 | 1 | .256 |
| [brand_cat=2] | -.846 | 1.1182 | -3.038 | 1.346 | .572 | 1 | .449 |
| [brand_cat=1] | 0[a] | . | . | . | . | . | . |
| [acc_att_cat=2] | -.224 | 2.8955 | -5.899 | 5.451 | .006 | 1 | .938 |
| [acc_att_cat=1] | 0[a] | . | . | . | . | . | . |
| (Scale) | 14.819 | | | | | | |

Dependent Variable: vib

Model: (Intercept), tool_pow_cat, job_cat, vib_cont_cat, brand_cat, acc_att_cat

a. Set to zero because this parameter is redundant.

**Parameter Estimates**

| Parameter | B | Std. Error | 95% Wald Confidence Interval Lower | 95% Wald Confidence Interval Upper | Hypothesis Test Wald Chi-Square | Hypothesis Test df | Hypothesis Test Sig. |
|---|---|---|---|---|---|---|---|
| (Intercept) | 1.946 | .7552 | .465 | 3.426 | 6.637 | 1 | .010 |
| [tool_pow_cat=3] | -4.807 | 1.2021 | -7.163 | -2.451 | 15.988 | 1 | .000 |
| [tool_pow_cat=2] | -3.258 | 1.5061 | -6.210 | -.306 | 4.679 | 1 | .031 |
| [tool_pow_cat=1] | 0[a] | . | . | . | . | . | . |
| [job_cat=5] | -3.060 | 1.3527 | -5.711 | -.409 | 5.118 | 1 | .024 |
| [job_cat=4] | -4.716 | 1.6045 | -7.860 | -1.571 | 8.638 | 1 | .003 |
| [job_cat=3] | -3.531 | 1.5887 | -6.645 | -.417 | 4.940 | 1 | .026 |
| [job_cat=2] | -.599 | 2.2731 | -5.054 | 3.857 | .069 | 1 | .792 |
| [job_cat=1] | 0[a] | . | . | . | . | . | . |
| [vib_cont_cat=2] | 5.896 | 1.2279 | 3.489 | 8.303 | 23.055 | 1 | .000 |
| [vib_cont_cat=1] | 0[a] | . | . | . | . | . | . |
| (Scale) | 35.075 | | | | | | |

Dependent Variable: vib

Model: (Intercept), tool_pow_cat, job_cat, vib_cont_cat

a. Set to zero because this parameter is redundant.